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Review Article

Nanotechnology and the food sector: From the farm to the table

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Abstract: The science of nanotechnology (NT) has been hailed as the new industrial revolution representing a new frontier of the 21st century. Defined as the control of matter at an atomic or molecular scale of between 1 and 100 nm, NT has been predicted to have a significant impact on society. While maintaining leadership in the competitive food market and food processing industry, NT has the capability of breaking down and manipulating foods, a seed, chemical pesticides and food packaging at the nano-scale level; and in so doing, is driving a nano-food and farming revolution. Apart from its promise to address climate change NT holds the potential of meeting global hunger. Today, consumers demand fresh authentic, convenient and flavourful food products. The future of new products and processes will witness the prolongation of their shelf life and freshness, improving the safety and quality of foods. NT therefore has the potential to revolutionise the food industry. Furthermore, this technology can be applied to develop nano-scale materials, controlled delivery systems, contaminant detection and create nano-devices for molecular and cellular biology.

Key words: Notechnology, agriculture, nano-food, food packaging, nano-particles

التكنولوجيا المتناهية الصغر (NT) وقطاع المواد الغذائية: من المزرعة إلى المائدة

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مدرسة التمريض والقبالة ،كلية الصحة والمجتمع ، جامعة سالفورد ، مبنى الارتن، شارع فردريك ، سالفورد م ٦ ٦ب ي، المملكة المتحدة

الملخص: لقد أعتبر علم NT ثورة صناعية جديدة تمثل الحدود الجديدة للقرن ٢١. كما تم تعريفه بالتحكم في المادة على المستوى الذري أو الجزيئي ما بين ١ و ١٠٠ نانومتر. ويتوقع أن يكون للNT تأثير كبير على المجتمع. للمحافظة على الريادة في السوق الغذائية التنافسية وصناعة تجهيز الأغذية فان للNT القدرة على التعامل مع الأغذية والبذور والمبيدات الكيماوية ومواد تغليف الأغذية على مستوى مقياس النانو. وعند حدوث ذلك ستظهر ثورة النانو الغذائية والزراعية. وبصرف النظر عن التصدي لتغير المناخ فان الNT تحمل في طياتها سد الفجوة الغذائية في العالم والقضاء على الجوع. يطالب المستهلكين اليوم بالمنتجات الغذائية الطازجة الأصيلة، المريحة ذات النكهة الممتازة. وسيكون من الممكن إنتاج هده منتجات باستخدام عمليات جديدة تؤدى إلى إطالة العمر الافتراضي للأغذية الطازجة، وتحسين سلامة وجودة الأغذية. للتكنولوجيا المتناهية الصغر NT القدرة على إحداث ثورة في صناعة المواد الغذائية. وعلاوة على ذلك، يمكن تطبيق هذه التكنولوجيا لتطوير مواد متناهية الصغر تستخدم في نظم التوصيل المتحكم به ، الكشف عن الملوثات وإنشاء أجهزة متناهية الصغر لعلوم الأحياء على المستوى الجزيئي والخلوي.

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Introduction

The aim of this article is three-fold: Firstly, it will provide a general overview of nanotechnology; secondly, it will discuss its potential application in agriculture and food systems; and, thirdly, it will highlight how some of the innovative developments in NT are likely to transform the food industry by revolutionizing food packaging and safety.

In writing this article, it seemed appropriate to remind ourselves of Theodore Schultz's acceptance speech for the 1979 Nobel Prize in Economics observing:

"Most of the people in the world are poor, so if we knew the economics of being poor we would know much of the economics that really matters. Most of the world's poor people earn their living from agriculture, so if we knew the economics of agriculture we would know much of the economics of being poor" (Shultz, 1979).

Thirty-two years on people in developing countries whose livelihood depends on agriculture are typically much poorer than those who work in other sectors of the economy and they represent a significant share, often the majority, of the total number of poor people in the countries where they live (Cervantes-Godoy and Dewbre, 2010).

The ever increasing global population is currently estimated to be close to 7 billion with 50% living in Asia (International Data Base, 2010) (Figure 1). As a consequence, this has led to the expansion of cities and township to accommodate people thereby leaving lesser area for agriculture. The gradual disappearance of fertile land across the world will inevitably affect food production and therefore meeting the needs of the world's burgeoning population is a challenge (Baruah et al., 2009). Unlike the developed countries where surplus food exists, a considerable number of people living in developing countries face daily food shortages as a consequence of environmental impacts and political instability. While the food industry in the developed countries is driven by consumer demand, the drive in the developing countries is to devise and implement strategies to facilitate drought and pest resistant crops to maximise yields. With limited availability of land and water resources, growth in agriculture can be achieved only by increasing productivity through good agronomy and supporting it with an effective use of modern technology. One such fascinating technology which holds the promise to impact on everybody's life is known as nanotechnology (NT).

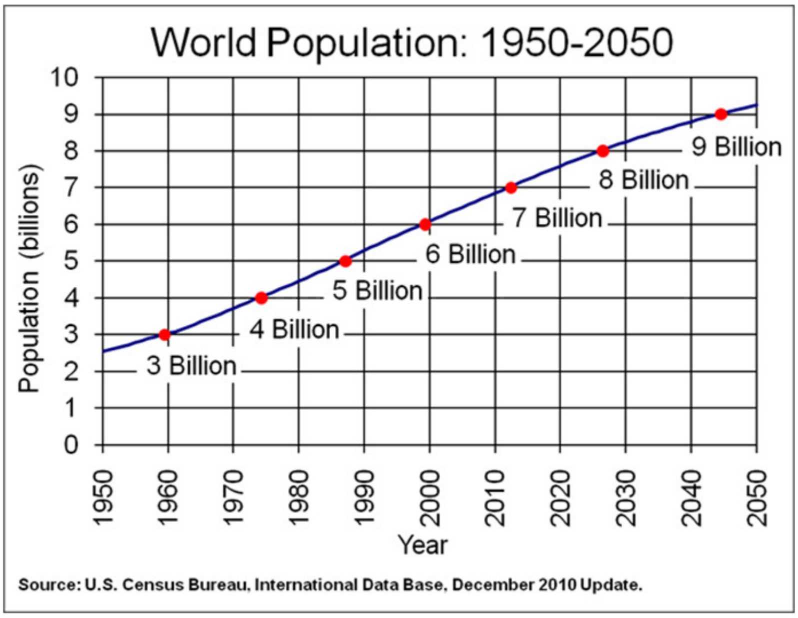


Figure 1. The predicted rise in the World Population: 1950-2050.

The potential of nanotechnology (NT) to revolutionise health care, textile materials, information technology (IT) and energy sectors have been generally well publicised in scholarly journals and communicated in the media. Investment in NT research and development has resulted in over 1000 nano-based products entering the consumer market (Project on Emerging Nanotechnologies (PEN), 2006). This tip of the NT iceberg products range from cosmetics, computer chips, sports goods and clothing, food and beverage, cross-cutting, construction, house-hold appliances, health and fitness, motor-vehicles to goods for children (PEN, 2006). Estimates suggest that by 2014 the value of NT products will exceed US$2,5 trillion (Lux Research, 2009). NT has also begun to find potential applications in the area of food. It has further been predicted that NT will transform the entire food industry and change the way food is produced, processed, packaged, transported and consumed (Sozer and Kikoni, 2009).

Understanding Nanotechnology

NT is defined as the design and manipulation of materials at the atomic and molecular scale (National Nanotechnology Initiative, 2008), with dimensions and tolerance limits of 0.1-100 nm (Riehemann et al., 2009). Utilising science at the nanoscale is not a new concept. For example, in the 4^{th} century A.D, the discovery of the Lycurgus cup left behind by the Romans was found to contain a minute amount of nanoparticles (NPs) of gold and silver causing the glass to look jade green in natural light and spectacularly red when a bright light is shone through it (Munroe, 2003). The reflection of light in such a novel way is effected by a minute amount of gold and silver in the glass.

Many may recall Isaac Asimov's science fiction novel, *Fantastic Voyage* from 1965. Here, a submarine had been scaled down to the size of a microbe and including a miniaturised crew, was injected into the blood stream of a scientist. This crew of scientists was able to successfully remove a blood clot from the brain of a famous physicist, and by this, guarantee his survival. At the time when Asimov wrote his novel, a famous physicist and winner of the Nobel Prize, Richard Feynman, made a historical claim. In his prescient 1960 talk, 'There's plenty of room at the bottom – an invitation to enter a new field of physics' Feynman proposed the use of machine tools to make smaller machine tools, and so on all the way down to the atomic level' (top-down approach to miniaturisation), noting that this is 'a development which I think cannot be avoided' (Feynman, 1960). In writing this article, it is wondered if indeed the film *Fantastic Voyage* and Michael Crichton's book, *Prey*, (Crichton, 2002) were in fact inspired by Feynman's speech and whether the report (Leary et al., 2006) on experimental nanoneurosurgery was also consequential to this dream.

As the 'science of the small' (Marchant, (2009) NT has been hailed as the 'next industrial revolution', promising to have a substantial impacts on many areas of our lives (National Technology Initiative, 2000; Maynard, 2006a). The prefix 'nano' originates from the Greek word 'nanos' meaning 'dwarf' and signifying 1 billionth of a meter (1 nm = 10^{-9}), which is invisible to the naked eye. To gain a sense of proportion (see figure 2) the double-strand DNA molecule has a diameter of 2 nm, the diameter of a human hair is approximately 100 000 nm while a red blood cell is 7000 nm in length. Atoms are smaller than 1 nm whereas molecules including some proteins range between 1 nm and larger (Whitesides, 2003).

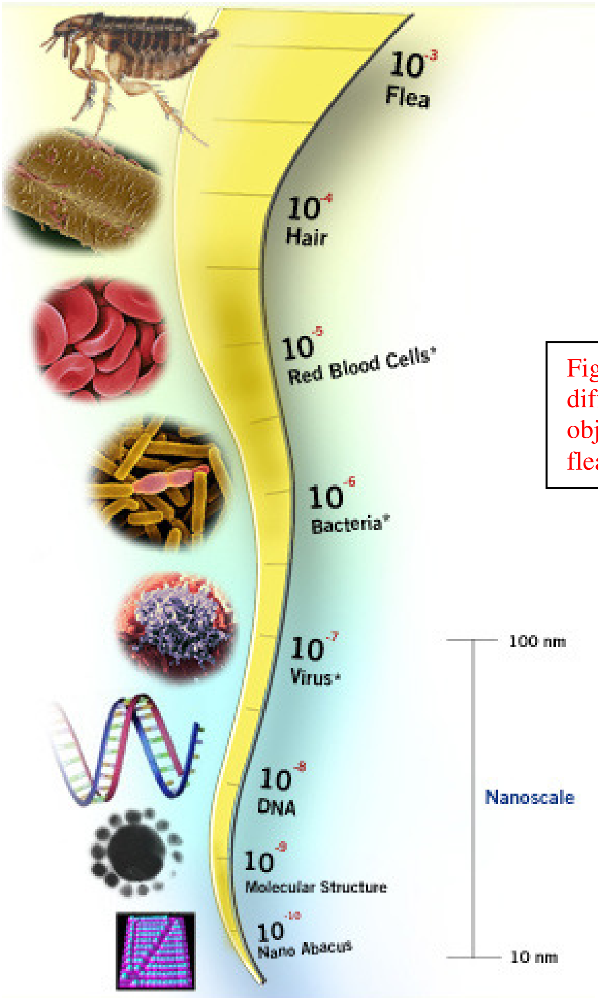


Figure 2: Scale depicting the dimensions of different nanometric and micrometric objects ranging from the nano abacus to the flea

Figure 2. Nanoscale objects.
[With kind permission: Dennis Kunkel Microscopy, Inc.]

In many ways the term 'NT' is arguably a misnomer since it represents more than one technology. Indeed this 21st century technology (Siegrist et al., 2006) is a multidisciplinary field undergoing explosive developments stemming from physics, chemistry, biology, biotechnology, neurology, Information Technology (IT) and engineering which branch into nanomedicine within human health care (ETC Group, 2003; Wilson, 2006).

Assembly Approaches in NT

The two main classificatory taxonomy, 'top-down' and 'bottom-up' approach applied in the synthesis of nano-engineered materials reflect how molecules are assembled to achieve the desired product (Figure 3). The scientific principle underpinning the 'top-down' approach relates to the physical process used in reducing a large block of material into nano-scale particles of desired shapes and sizes as well as the manufacture of other distinctly new materials such as carbon nanotubes, bucky balls and quantum dots (QDs) (Maynard, 2006a). When compared to the same material in its bulk form, nano-scale particles exhibit uniquely different and novel properties in the context of chemical reactivity, bioactivity to absorption capacity (Hunt and Mehta, 2006). This behaviour occurs because smaller particle size increases the size of the molecules (Royal Society and Royal Academy of Engineering, 2004).

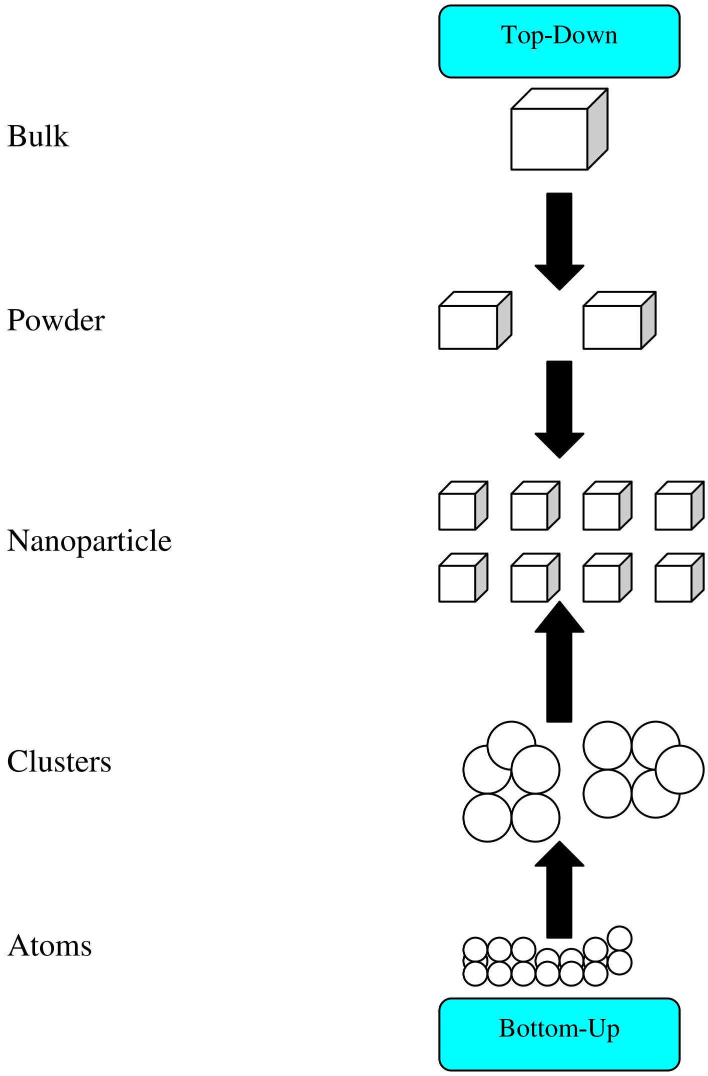


Figure 3. Top-down and bottom-up assembly approaches in nanotechnology.

The epitome of 'bottom-up' processing technologies is underpinned by the knowledge of cell biology (Zandonella, 2003). The concept of self-organization has existed from the moment life was started on earth. Nature has evolved many bio-organic molecules that form complex structures with equally complex behaviour, known as the living cells. These cells have the capability to self-assemble (Liu et al., 2003) and develop further complex structures culminating in such intelligent life forms as the human and animal kinds. Even in instances when living cells sustain damage, nature has an amazing ability to heal itself by self-organization. For example, following a trauma as in surgery, the body responds by sending white blood cells which attack any invading pathogens to prevent infection while red blood cells and proteins seal the wound and provide nutrients to new cells which act as a replacement of the damaged ones. These custom-made bio-materials have inspired scientists to design materials that are ideal for a specific application (bottom-up) rather than to cut and trim these naturally occurring phenomena to suit their needs. The 'bottom-up' approach therefore begins by designing and synthesizing custom-made molecules that possess the ability to self-replicate. These molecules are then organised into higher macro-scale structures. Self-replication is often triggered by a change in temperature, pressure, and application of electricity or a chemical. Monitoring of self-replication is considered critical to prevent the 'grey goo' effect (Silva, 2004). This term refers to the fear that nano-technological devices will either be programmed to self-replicate, or they will 'evolve' into devices capable of self-replicating and destroy the natural world (Phoenix and Drexler, 2004).

Agriculture Contextualised

People in developing countries continue to depend on agriculture for their living. Indeed agriculture represents the backbone of economy for most developing countries, within Africa, Latin America and Asia, with more than 60% of the population being reliant on it for their livelihood (Warad and Dutta, 2007). Research in agriculture has always dealt with improving the efficacy of crop production, food processing and food safety, environmental consequences of food production, storage and distribution (Vernikov et al., 2009; Sozer and Kokini, 2009). Given the current depletion rate of natural resources NT is therefore held out by many as the 'Holy Grail' for a sustainable future for the agricultural and food sectors and therefore a self-sustainable world. Arguably a development of this nature is only possible if there is an equitable distribution of technological innovations across the world to prevent the nano-divide (Mehta, 2002). Nevertheless, despite the voices of concern warning of the possible negative consequences or risks of NT, proponents argue that this new technology will be beneficial to everyone, including the poor. In light of this, the recent United Nation Millennium Project Report, Task Force on Science, Technology and Innovation (Calestous and Yee-Chong, 2005) proposed that NT will be important to the developing world because it harbours the potential to transform minimal work, land and maintenance inputs into highly productive and cheap outputs; and it requires only modest quantities of material and energy to do so. However, these same qualities could be perceived as being harmful because poor countries have abundant labour, and, in many cases, land and natural resources. In this way, major corporates supporting NT may be powerful enough to cause displacement of people and disruptions in the economies of poorer nations.

Currently, nanotechnologies are being applied across a range of industries including military, energy, pharmaceuticals, medicines and cosmetics. Knowledge gained from these disciplines could be easily adapted for use in food and agriculture products, particularly its applications in food safety (detecting pesticides and micro-organisms), in environmental protection (water purification) and in the delivery of nutrients (Roco, 2003; Ulijn, 2007).

NT and Agriculture

NT has the potential to revolutionize the agricultural and food industry through precision farming with the aim of maximising crop yields while minimising the use of chemicals such as fertilisers, pesticides and herbicides through monitoring of environmental variables and applying targeted action. It is anticipated that precision farming will make use of computers, global satellite positioning systems (GPS) and remote sensing devices to measure local environmental conditions and determine if crops are growing at maximum efficiency or identifying the precise nature and location of any problems. The use of centralised data has the added advantage of determining soil conditions, plant developments, seeding, fertilizer, chemical and water use in a finely-tuned manner to reduce production costs and potentially increase output which collectively will benefit the farmer (Rickman et al., 2003). This approach to farming can assist in reducing agricultural waste thereby keeping environmental pollution to a bare minimum. A further distinct role of NT-enabled devices will be the increased use of autonomous sensors linked to a GPS system for real-time monitoring. These wireless sensors which are already being used, for example in the Californian vineyards, Pickberry (USA) in Sonoma County and in Australia could be scattered throughout the field so they could monitor soil nutrient conditions and crop growth as well as the early detection of such potential problems as pest attacks (Millman, 2004; ETC Group, 2004).

Biotechnology further offers the prospect of agricultural yields otherwise challenged by concerns of arable land and reduced water irrigation. For example, development in plant tissue culture for gene transfer has enabled scientists to produce entire growing plants from just a few cells (Burne, 2006). Using the soil-dwelling bacterium Agrobacterium is a common way to generate genetically modified plant cells. On contact with a plant wound, agrobacterium transfers some of the deoxyribonucleic acid (DNA) in to the plant cells exposed by the wound with the eventual aim of producing entire plants.

The second half of the 20th century witnessed an increased use of pesticides, including DDT. These substances were found to have toxic effects on human and animal health as well as the ecosystems and consequently banned from use. Instead crop yields were maintained through the traditional methods of crop rotation with biological pest control methods. In the future however technologies encapsulation techniques and controlled release methods will revolutionize the use of pesticides and herbicides. Depending upon certain specific conditions, such as moisture and heat levels, pesticides could be released slowly or quickly (Zhang et al., 2006; Syngenta, 2007). NT also holds the potential of removing the harmful effects of highly toxic pesticides through a degradation process known as photocatalysis (Warad and Dutta, 2007). During photocatalytic reaction, harmful substances for example, persistent pollutants pesticides, are disintegrated into harmless compounds. Degradation through photocatalysis has also gained popularity in the waste water treatment process (Hermann, 1999), for purification, decontamination and deodorisation of air (Peral et al., 1997).

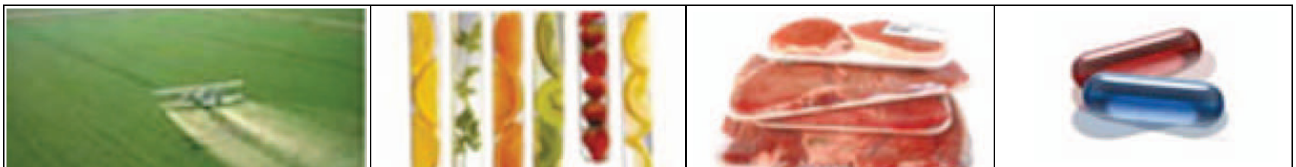
Nano-Food Industry and Financial Implications

The term 'nano-food' describes food that has been cultivated, produced, processed or packaged using NT techniques or tools, or to which manufactured nano-materials have been added (Chaudhry et al., 2008). Over the centuries, food has undergone a variety of post-harvest and processing-induced modifications that affect its biological and biochemical make-up so that development of NT in the field of biology and biochemistry could well further influence the food industry (Shrivastava and Dash, 2009).

Research and development has indeed envisioned that NT will transform the entire food industry thus changing the way nano-food is produced, processed, packaged, transported and consumed (Figure 4) (Joseph and Morrison, 2006).

In recent years NT has developed into a wide-ranging multibillion dollar industry. The presence of NT on the global market is widely expected to reach 1 trillion US$, with approximately 2 million workers (Roco and Bainbridge, 2001). Based on the number of patent applications NT has also started to make an impact on different aspects of the food and associated industries (Chen et al., 2006). In fact the worldwide sales of NT products to the food and beverage packaging sector rose from US$150 million in 2002 to US$860 million in 2004 (Verbeke, 2006). A report by Helmut Kaiser Consultancy (2004) estimated that the nanofood market would escalate from US$2.6 billion in 2005 to US$7 billion in 2006 and thereafter to US$20.4 billion in 2010 (Figure 5).

On the other hand, the findings by a consulting firm, has valued the application of NT to food at around US$410 million (food processing US$100 million; food ingredients US$100 million and food packaging US$210 million) with an increment prediction of US5.8 billion by 2012 (food processing US$1303; food ingredients US$1475 million; food packaging US$2930 and food safety US$97 million) (Cientifica, 2006). The findings further stated that there are already around 400 food and beverage companies ranging from Altria, Nestle, Kraft, Heinz, Unilever to small nanotech start-up companies who are applying nanotechnologies in their products (Cientifica, 2006) and that such application will increase dramatically in the near future (Chaudhry et al., 2008).



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

Figure 4. Potential applications of NT in the food and food-packaging industries.
[With kind permission: Michael Berger. http://www.nanowerk.com/spotlight/spotid=1846.php]

The food industry is clearly under intense pressure to improve food safety and achieve profit margins (Dingman, 2008), enhance nutritional values, freshness, new tastes, flavours, textures, reduce costs as well as to increase the shelf-life and traceability of their products (Sekhon, 2010). In improving taste, the industry is also aiming to reduce salt, sugar, fat and preservatives and address food related conditions, for example, obesity and diabetes (Cientifica, 2006).

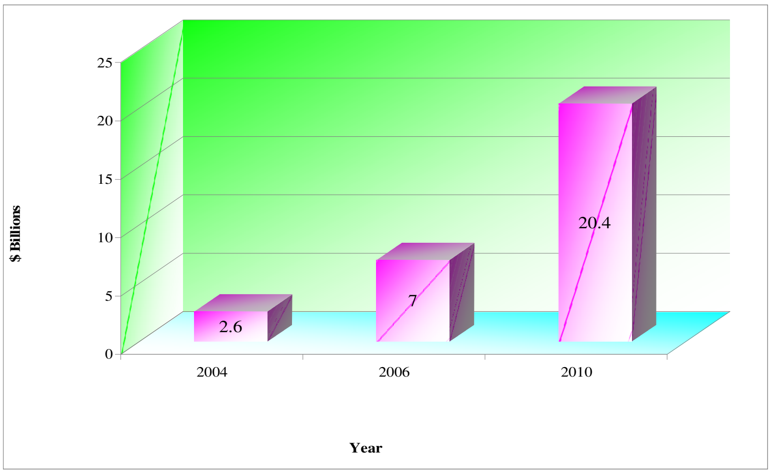


Figure 5. Financial turnover of world nanofood market.
Helmut Kaiser Consultancy (2004).

Application of NT to Food

Food technology is therefore perceived as being one of the industry sectors where NT will play a crucial role in the future. Ongoing technological development in manipulating the molecules and atoms of food means that the future of food industry has a powerful method to design food with much more capability and precision, lower costs and sustainability (Ravichandran, 2010).

Currently a major focus of NT applications in food is the development of nanostructured or nanotextured food ingredients and delivery systems for nutrient and supplements. In a relentless attempt to achieve this objective, a variety of processes ranging from nano-emulsions, surfactant micelles, emulsion bi-layers and reverse micelles are being utilised (Weiss et al., 2006). The development of these nano-structured ingredients is underpinned by the claim that they offer improved taste, texture and consistency (Cientifica, 2006). For example, low fat nano-structured mayonnaise, spreads and ice-creams are in fact as 'creamy' as their full fat alternatives and they further claim to offer a healthier option to the consumer.

A number of nano-micelle based carriers for nutraceuticals and nutritional supplements are currently available and have been subject to discussion (Kuzma and VerHage, 2006) while BioDelivery Sciences International (2010) have introduced the nanocochleate system designed to protect micronutrients and anti-oxidants from degradation during manufacture and storage. The recent development of self-assembled nanotubes from the naturally occurring hydrolysed milk protein α-lactalbumin is claimed to act as a carrier for nanoencapsulation of nutrients, supplements and pharmaceuticals (Graveland-Bikker and de Kruif, 2006).

Nanoencapsulation in food ingredients and additives is another area of development in NT, particularly as an interactive idea which would allow consumers to modify food depending on their own nutritional needs and tastes. The concept reflects thousands of nanocapsules containing flavour or colour enhancers or added nutritional elements (such as vitamins) which would remain dormant in the food and released only when triggered by the consumer at a particular microwave frequency (Dunn, 2004).

NT and Food Packaging

One of the most promising innovations in smart packaging (see figure 4) is the use of NT to develop antimicrobial packaging to prolong product shelf-life (Cientifica, 2006) and reducing man-made preservatives has been the goal of many companies (Sekhon, 2010). Packaging that incorporates nanomaterials can be 'smart' meaning that it can respond to environmental conditions or repair itself or alert the consumer to contamination and/or the presence of pathogens (Baeumner, 2004). This approach to packaging systems aims to respond to such environmental conditions as temperature and moisture (Cientifica, 2006). In providing solution for these, NT can modify the permeation behaviour of foils, increasing barrier properties, for example, mechanical, thermal, chemical and microbial, improving mechanical and heat-resistance properties, developing active anti-microbic and anti-fungal surfaces and sensing as well as signalling microbiological and biochemical changes (Cientifica, 2006).

There are many other organizations involved in developing 'smart packaging'. For example, in collaboration with researchers at Rutgers University, in USA, Kraft Foods is engaged in developing the 'electronic tongue' for inclusion in packaging. This comprises of an array of nanosensors which are sensitive to gases released by food as it spoils, and consequently causing the sensor strip to change colour thus giving a clear indication whether the food is fresh or not. Kraft Foods is also producing products which incorporate nanosensors which detect a consumer's food profile of likes and dislikes, allergies and the person's nutritional deficiencies. NT could then respond by releasing accurately controlled amounts of suitable molecules to tailor the smell, taste and goodness of the product for the individual consumer.

The aim of food packaging film is to prevent the drying out of the contents and to protect them from moisture and oxygen. Bayer Polymers has developed the Durethan KU2-2601 packaging film which is lighter, stronger and more heat resistant than the one currently available on the market. Known as the 'hybrid system, the new film is enriched with a vast number of silicate particles to prevent the entry of oxygen and other gases and the exit of moisture, thus preventing spoilage of food (Sekhon, 2010).

Nanocomposites and Food Packaging

In ideal conditions, breweries would prefer to use plastic bottles to ship beer as these are lighter than glass and cheaper than metal cans. Under normal circumstances, alcohol in beer would react with the plastic used in the bottle thereby shortening the shelf-life. In association with Nanocor, Voridan has developed a nanocomposite containing clay particles called Imperm which makes the bottle stronger and lighter and less likely to shatter. Furthermore the loss of carbon dioxide from the beer and the ingress of oxygen into the bottle are minimised, thus maintaining the freshness of the beer and giving it a six-month shelf-life (Asadi and Mousavi, 2006).

Similar technology is also being developed for the US government as a means of detecting possible terrorist attacks on the US food supply (Ravichandran, 2010). Scientists in the Netherlands are taking smart packaging a step further with nanopackaging that will not only sense when food is beginning to spoil, but will release preservatives to extend the life of food. According to industry analysts, the current US market for 'active, controlled and smart' packaging for food and beverages is estimated to be US$38 billion. This has been predicted to surpass US$54 billion by 2015 (Ravichandran, 2010).

NanoBioluminescence Detection Spray

Other organizations are exploring ways in which NT can offer improvements in sensitivity or ease by which food contamination can be detected. AgroMicron, for example, has developed the NanoBioluminescence Detection Spray, which contains a luminous protein engineered to attach itself to the surface of microbes such as *Salmonella* and *E. coli*. Once bound, it emits an observable glow thus allowing easy recognition of contaminated food or beverages in that the more intense the glow the higher the bacterial contamination. Currently the company is designing new spray techniques which will be applied in ocean freight containerised shipping as well as to fight against bioterrorism (Moraru et al., 2003). Other innovations include the development of nano-scale dirt repellent coatings possessing a 'Lotus Effect', a term referring to water droplets forming beads on the surface of lotus leaves due to nano-scale wax pyramids. Its potential use for self-cleaning surfaces will prove beneficial in abattoirs and meat processing plants (Garland, 2004).

Among the near-market developments are the nanomaterial-based next-generation packaging displays that include Radio Frequency Identification Display (RFID). Developed by the military more than 50 years ago, RFID has now found numerous applications from food monitoring in shops to improving supply chain efficiency. Comprising of microprocessors and an antenna that can transmit data to a wireless receiver, this technology can be used to observe an item from the warehouse to the consumer's hands. Unlike bar codes, RFID tags do not require line-of-sight for reading and it has the potential of reading hundreds of tags a second (Cientifica, 2006). This kind of technology has been tested by retail chains like WalMart, Home Depot, Metro group and Tesco.

NT, and Food Contamination

There is growing concern that the increased use of materials, products and application of NT may present with new indirect sources of food contamination. Such risk of exposure may arise from the use of nano-sized pesticides and veterinary medicines, contact of food with nano-particulate-based coatings during preparation or processing, or potential migration of nano-particles from food packaging (Chaudhry et al., 2008). The three possible known routes for NPs to enter the body and potentially cause harm include dermal exposure, inhalation and ingestion (Chi-Fai et al., 2007).

As a general rule, the normal epidermis could potentially provide an excellent protection against nano-structured (Nel et al., 2006). However, the findings from some studies suggest that it can in fact penetrate the stratum corneum and thereafter into the dermis and subsequently translocate to the regional lymph nodes and general blood circulation (Tinkle et al., 2003; Oberdörster et al., 2005). Pulmonary toxicity or pathogenic manifestations is said to be determined by the particle size, mass, chemical composition, sample types, rates of deposition and clearance of inhaled materials (Maynard, 2006b). However, the current state of knowledge does not provide generic conclusion about toxicity relating to size alone. It is therefore important that potential toxicity of each nanomaterial be evaluated on a case-by-case basis (Health and Safety Executive (HSE), 2006). The potential effects of NPs through the gastro-intestinal tract (GI) route are largely unkown. The application of NT in food and drink has therefore led to concerns from a growing body of scientific evidence which indicates that free engineered NPs can cross the cellular barriers and their subsequent harmful effects can be hazardous to consumers' health (Oberdörster et al., 2004, Donaldson et al., 2004; Geiser et al., 2005). The findings from an in vitro study on human cell cultures using fluorescence-labelled silicone dioxide (SiO_2) (Chen and Mikecz, 2005) have demonstrated that NPs less than 70 nm could enter cell nuclei and therein causing accumulation of protein as well as impairment of DNA replication and transcription. Whether the use of SiO_2 as an additive to food and food packaging will cause comparable in vivo effects appears to be unknown.

Although each of the three main constituents of food, namely proteins, carbohydrates and lipids follow a different digestive pathway, they nevertheless share a common factor in that the digestion of their constituents occurs at the nanoscale. This would imply that the processing of foods at the nanoscale level would simply improve the speed or efficiency of their digestion, uptake, bioavailability and metabolism in the body (Chaudhry et al., 2008). Indeed within the nutrition market there are already supplements claiming to contain di and tri peptides and thus being more readily digestible (Crisalle, 2007). In contrast it could be argued that since the processing of substances to this scale often alters their properties, then nano-scale processing of foods may well alter how the food ingredients 'behave' upon breakdown within the gut and as a consequence, how they are treated in the GI tract. Further research into this important issue will also answer regulatory questions.

Regulations and Nanofood

There is no doubt that research and development in the application of NT in food and food packaging is growing at an unprecedented rate. Currently, however, there is no statutory or regulatory standard which requires the labelling of food products containing NPs. Within the market place, different terms such as nanofood and ultrafine food have been used, whereas it is difficult to identify which merchandise is called 'nano'. According to the Institute of Food Science and Technology (IFST) (2006) consumers in Europe are unlikely to be aware of NT applications in foods. However, many manufacturers in Asia, for example, mainland China, Taiwan and Hong Kong, intend to use these terms to emphasize the fineness of components for commercial and marketing purposes as well as to avoid misleading the public. Penalties are issued when regulations are not observed. The Department of Health (DOH (2006), for example fined manufacturers in Taiwan for falsely claiming that their products contained 'ultrafine foods' or 'nanofood' with exaggerated physiological functions.

The potential risks arising from exposure to different types of NPs are as yet not fully understood. In the absence of clear definition, public debate, food safety assessments and effective food regulations, the allowing of NT-based food products, namely nanofood, to reach the food markets is likely to jeopardize the benefits of nanotechnologies to the food industry (IFST, 2006). As a step toward developing the regulatory standard, it is imperative to consider several factors, namely particle size, range and measurement, processing, physicochemical properties, safety and risks. Furthermore it is necessary to realise that the technology may offer diverse applications that will touch multiple regulatory agencies, and also to consider whether the government should in fact regulate the process or the product (Jones, 2006).

Public Concerns

As evident with genetically modified (GM) foods, public perception of NT is another critical factor likely to determine the future direction the food industry will take (Cobb and Macoubrie, 2004; Lee, 2005; Ravichandran, 2010). While some foods engineered by NT are likely to be more readily accepted than others, nonetheless the benefits of foods derived from NT need to be explained to the consumers. A recent survey undertaken by Siegrist et al. (2007) evaluated the public perception of different types of food materials, including an anti-bacterial food packaging material, a nano-coating that protects tomatoes from humidity and oxygen, a bread containing nanocapsules of omega-3 fatty acids, and a juice containing vitamin A encapsulated in starch. The findings obtained from a sample of 153 people showed that the NT-derived packaging was perceived as being more beneficial than the NT-engineered foods. These results also supported the hypothesis that NT inside a food was perceived as less acceptable than being on the outside, as in food packaging. However, consideration must be given to the social and ethical aspects of using NT in the food sector. Currently, the potential risks of nanomaterials to human health and to the environment are unknown (Dowling, 2004). The 2006 report of the IFST suggests that 'size matters' and recommends the use of NPs in the food sector only after safety has been proved following vigorous testing. Taking lessons from the GM arguments across European countries, it is vitally important to keep the public informed and involved by discussing the benefits and risks of this highly promising technology. Governments should even consider appropriate labeling and set down regulations that will facilitate an increase of consumer acceptability.

Conclusion

NT is fast becoming every nation's future. The diverse nature of nanotechnologies may well mean that several decades will elapse before their effects are felt fully. Consequently NT is most likely to co-exist with established technologies rather than suddenly replace them. Since the process of innovation and the diffusion of benefits into society are not fully understood, it is necessary for researchers such as social scientists to examine the possible impacts and potential of NT on society because differential rates of diffusion may well create a 'nano-divide'.

The application of NT in agriculture and food systems holds tremendous benefit to society. For example, there are promising results being developed in such areas as food packaging and food safety. However, evidence relating to the potential health risks that may arise from the consumption of nano-foods and drinks is sparse. Much of the available data relates to inhalation toxicology and engineered NPs leaving major knowledge gaps in respect of behaviour, fate and effects of nano-sized food ingredients and additives via the GI route.

The uncertainties created by limited available knowledge are likely to provoke public concern in the future. Like any new technology, public confidence, trust and acceptance are likely to be the key variables determining the success or failure of NT-based foods. It would therefore seem prudent for the industry to adopt a pro-active approach in forming forums aimed at tackling the issues through regularly informing, engaging and consulting the consumers. One of the contentious but important issues in this regard is that of the labelling of foodstuffs that are products of NT. The food industry could pave the way by voluntarily declaring the use of nano-additives, particularly where free engineered NPs have been introduced in food and drink and where such products are likely to be consumed in large quantities and/or by a large proportion of the population.

The incorporation of NPs into food packaging is expected to improve the barrier properties of packaging materials and should thereby help to reduce the use of valuable raw materials and the generation of waste. For the poor, however, socio-economic structure is a much more difficult barrier to overcome than technological innovation. Nanotechnology, even where fully integrated in developing countries, may not necessarily change these socio-economic structures; instead, it could serve to exacerbate existing gaps and further the technological and socio-economic isolation of the poor thus creating inequalities between 'nano haves' and 'nano have nots'. Perhaps, then, consideration ought to be given for NT to be tagged with a label to constantly remind scientists and governments of the need for its wise, responsible, sustainable and equitable application for the good of humankind throughout the world.

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