MINISTRY OF AGRICULTURE, FISHERIES AND FOOD **CSG 15**

Research and Development

Final Project Report

(Not to be used for LINK projects)

Project title	Nanotechnology in the food chain industries
MAFF project code	**CSA 5875**
Contractor organisation and location	Silsoe Research Institute Wrest Park, Silsoe, Bedford MK45 4HS
Total MAFF project costs	£ 5000
Project start date	01/09/01
Project end date	28/02/02

Executive summary (maximum 2 sides A4)

The Potential Impact of Nanotechnology on the Food Chain Industries

D M Bruce, Head of Biomaterials Group, Silsoe Research Institute, Wrest Park, Silsoe Bedford, MK45 4HS, UK

Executive summary

1. Nanotechnology is a growing area of research worldwide, and R&D budgets are already large. All aspects of nanotechnology research are very active. Developments expected from this research are already arriving in the marketplace, and will become more widespread and pervasive.

2. This paper is a forward look at the potential impact of nanotechnology on the food chain industries, based on published material. Owing to the speed of advances being made in nanotechnology, a review based on published material cannot be completely up to date in all areas.

3. The timescale of the forward look was chosen by the author as up to 10 years. Further ahead, the developments from nanotechnology were considered to be even more uncertain, and potentially so major as to affect many aspects of life.

4. The main research topics in nanotechnology are not directed at, or directly relevant to food industries, with the exception of biotechnology, in which nanobiotechnology is as yet a small element. The potential relevance to the food chain industries therefore arises via the potential of developments in nanotechnology to be applied in a range of industries.

5. Having considered a wide range of published information on research in nanotechnology topics and developments that may come from it, three topics are proposed in which developments arising from nanotechnology are likely to impact on food chain industries, namely Sensors, Health and Food, and

Materials. In each topic, nanotechnology is only a small, though increasingly important, element of the overall research activity.

6. The Sensors topic is driven by consumers' concerns with 'quality' and an expected demand for information on the presence of desirable attributes and the absence of undesirable ones, for particular food items at the time of purchase and of consumption.

7. Health and Food as a topic is driven again by the consumer, arising from the link between health and food/ diet, and in particular, driven by the potentially long and healthy life that may be possible *via* developments in biomedicine. This is particularly so in the case of parents considering food for their children.

8. The Materials topic arises from the importance of materials in (a) aspects of food hygiene, (b) effective and long-lasting machinery for manufacturing, and (c) active or 'smart' packaging of foods. The first of these is also of importance to healthcare industries, and the second to almost all manufacturing, not just of food.

9. Given that the research is not being pursued with the food industries in mind, for the food chain industries to be able to exploit those developments, there will be a need for activity to take the advances made by nanotechnology research and develop from them technology specific to the needs of the food chain industries. In some cases the activity may involve further nanotechnology research, but development of systems to interface with and exploit nanotechnology elements in a food context will be required a major requirement.

10. Although nanotechnology has the potential to impact on the food chain industries, other research topics will also have impact and the relative importance of nanotechnology in relation to other research topics has not been considered in this paper.

11. It is suggested that
    A. There is a need for continuing scanning of the nanotechnology horizon, with a particular need in the topics of Sensors and Materials, to evaluate nanotechnological research and development in relation to DEFRA's aims and objectives. This would aim to identify needs for further research and development that would enable exploitation for the benefit of the industries that DEFRA serves.
    B. Two such needs, appropriate to the food chain industries, are
    ? systems to exploit nanotechnological developments in sensors, and
    ? exploitation of material surfaces that are fundamentally less hospitable to bacteria important in food hygiene.

Scientific report (maximum 20 sides A4)

The Potential Impact of Nanotechnology on the Food Chain Industries

D M Bruce, Head of Biomaterials Group, Silsoe Research Institute, Wrest Park, Silsoe Bedford, MK45 4HS, UK

What is nanotechnology?

Nanotechnology can best be considered as a 'catch-all' description of activities at the level of atoms and molecules that have applications in the real world. The prefix *nano* (from *nanos*, Greek for dwarf) means one-billionth (10^{-9}) of something, as in nanometer, abbreviated to nm. So a nanometre is a billionth of a metre, that is, about 1/80,000 of the diameter of a human hair, or 10 times the diameter of a hydrogen atom.

Working definitions of nanotechnology, include "*that area of science and technology where dimensions and tolerances in the range of 0.1nm to 100 nm play a critical role*", and "*a technology able to inexpensively fabricate most structures consistent with natural law, and to do so with molecular precision.*"

What does nanotechnology offer?

In essence, nanotechnology promises devices and materials with greater functionality and novel properties, perhaps using less raw material and less energy. There is no existing market demand for "nanotechnology," as such, but a great demand for what it could do. People want better medical care, food, housing, consumer goods, transportation, education, etc., preferably at lower costs, with greater safety, in a cleaner environment. Nanotechnology holds the promise of big steps in the direction of better quality *and* lower costs *and* increased safety *and* a cleaner environment.

What are the key concepts in nanotechnology?

The physical properties of matter are highly size-dependent.
From simple physical principles, it is clear that nanoparticles will exhibit phenomena not available with 'normal' materials, thus making possible new applications. Finer grain sizes can produce denser materials with greatly improved mechanical properties or unusual combinations of properties, e.g. harder and less brittle. Chemical activity also increases; the smaller the particle, the larger the area of active surface per unit mass. For the same reason, reaction rates in nanolitre quantities of materials are orders of magnitude faster, making possible advances in speed and convenience via the "lab on a chip". Miniaturising the analytical process has the benefit of both reducing the costs of analysis, as well as dramatically speeding it up, making it possible to identify a disease or pollutant within minutes. Optical, electronic and magnetic properties are also size-dependent, allowing devices with new properties to be developed. In materials that, in bulk form, exhibit phase transitions, small perturbations can be made to give rise to large responses. Together, the physical and chemical properties of nanostructured materials allow new types of detectors and sensors to be developed. At 'extreme' nanotechnology, quantum effects become more evident, already being exploited through new techniques in microscopy.

Surface forces predominate in small or ultra-thin assemblies
Thin films or monolayers usually range from 1nm to 5nm thickness but may be only one molecule or even one atom thick in some cases. They can be organic or inorganic, and have a wide range of properties, from being chemically active to being wear resistant. It is also possible to make new types of nanocomposites or organic/ inorganic hybrid structures by depositing or attaching organic molecules to ultra-small particles or ultra-thin man-made layered structures known as superlattices.

Computation
Because nano-structures contain few atoms, relative to most materials, they are uniquely susceptible to high-level simulation using computers to investigate the properties of the structures from principles of basic physics, and to design materials with desired properties.

Merging of scientific disciplines
Physics, chemistry and biology merge into one at the nanoscale.

Top-down and bottom-up.
The two fundamentally different approaches to nanotechnology are termed 'top down' and 'bottom up'. The *top-down* approach to nanotechnology essentially consists of making things that already exist on the micrometer scale, even smaller by a factor of one

thousand or so. This line of development has been followed with some success both in microelectronics and in microelectromechanical systems (MEMS), and devices such as the small accelerometers now used in airbags, have been produced. *'Bottom-up'* or '*molecular manufacturing'* is building structures atom-by-atom, or molecule-by-molecule. Nanotechnology is often identified with the idea of handling individual atoms, of building nanoscale systems atom by atom. To result in anything useful, 'assemblers' will have to be developed to automate this task.

Nanotechnology matches the scale of life processes.
Because the nanoscale is small enough to work within the mechanisms of living cells, technological developments at a cell scale are made possible. The term 'nanobiotechnology' is used to describe nanotechnology that relates to mechanisms of the living cell.

Self-assembly
In the development of nanotechnology, the construction principles used by cells may be more important than those governing the direct manipulation and positioning of atoms. The cell makes a small set of small molecules that self-assemble into macromolecules (e.g. DNA, proteins). Even macromolecules can self-assemble to make higher structures because the macromolecules have exact shapes and binding preferences. The protein factory of the cell for instance, can self-assemble from a mix of more than 50 different molecular units. Self-assembly principles may in principle be applied to inorganic molecules, to create structured materials and devices. The environment may be crucial, as the behaviour of a small quantity of self-assembling molecules is strongly influenced by the way they are attached to a surface.

What are the major areas of nanotechnology in which developments are in progress?

The whole of this field is active, with massive research programmes underway in the USA, Germany and Japan in particular, much of it at the fundamental level. The work can be categorised as follows.

Nanofabrication encompasses the making of things with dimensions less than 100 nm.
Nanometrology is the precise measurement of structures fabricated with dimensions less than 100 nm.
Functional nanotechnology describes applications in which nanostructures are used to produce improved optical, electronic and magnetic properties.
Nanomachines are an extension of the present day micromachines and microactuators into the nano world.
Molecular nanotechnology is the technology of molecular sensing and molecular recognition, and reflects the interface between the biological and inorganic systems. Design of molecules with specific shapes and properties from the basis of understanding becomes possible. Biomimetics is taking inspiration from nature's techniques as a basis for creating materials with novel properties.
Nanostructured materials in which the grain and composite size is less than 100 nm, offer the potential for materials that are stronger and have better wear- and corrosion-resistance, and other properties, and particles, clusters and catalysis on the nanoscale promise new and improved properties.
"Extreme" nanotechnology includes manipulation and assembly of individual atoms and molecules.
Computer Modelling and Simulation at the atomic level, to predict and design the chemical and physical properties of novel materials.

Are nanotechnology developments feasible?

The following examples have been collated to illustrate the range of possibilities. Even though much of the research is at a very early stage, the following predictions, which include some from the 'Foresight' Materials Panel, suggest that some nanotechnology developments relevant to the food industries are already well advanced.

Applications that may come on-stream within the next 5 years include:

? 'Smart' wrappings for the food industry that indicate freshness or otherwise
? New sensors for applications in medicine, environmental monitoring and in the preparation of pure chemicals and pharmaceuticals
? Better photovoltaic techniques for renewable energy sources
? New lighter and stronger materials
? Display technologies for better, lighter, slimmer and flexible screens
? 'Lab-on-a-chip' diagnostic techniques
? Drug delivery systems for human and animal uses
? Glasses with scratch-resistant coatings
? Tracking individual molecules within a functioning cell, using quantum dot nanocrystal tags, without significantly interfering with cellular physiology
? Dlivery of drugs by controlled means
? Chips for rapid analysis of DNA and other biomolecules

? New biocompatible materials for use in teeth, bone or other tissue replacement

Applications that may come on-stream within the next decade include:
? Anti-corrosion coatings
? Tougher and harder cutting tools
? Plastic electronics - flat panel displays
? Molecular sieves for faster and more selective filtration
? The capability to map an individual's entire genetic code almost instantaneously
? Drugs that are designed rather than discovered
? Diagnosis and therapy for disease based on DNA profiles of individuals
? Smart materials (thin but strong coatings with novel functions including acting as environmental sensors, photoelectric cells, image screens)
? Molecular motors for driving machines at the nano-scale

Those still at the stage of speculation and at least 10 years and perhaps 25 years away.
? Nanostructured materials that are much more durable and uniform.
? Ultra high-density electronic memories and ultra fast processors
? Nanomachines or medical applications in which tiny machines circulate in the bloodstream cleaning and repairing our bodies
? The ability to extend human life perhaps by 50% from present expectations
? artificial neural implants
? Biocomputers and potential integration of living beings with computers
? Molecular design of materials
? Construction and recyclability of any product through some kind of molecular (dis)assemblers

Recent developments reported in the press that illustrate the potential relevance of nanotechnological developments to the food chain industries

An entirely new class of drugs is being developed that kill bacteria, even those that have developed resistance to antibiotics. Dr Ghadiri of Scripps Research Institute, La Jolla, California, found that, if rings of eight amino acids, the molecular building blocks of proteins, are placed near cell membranes, they self-assemble into tubes within those membranes. The tubes are about three nanometres in diameter and six nanometres long, big enough to puncture a cell membrane. The result is that many of the cell's critical components squirt out, and it dies. Dr Ghadiri found several of these 'octets' that were particularly effective against the antibiotic-resistant strain of *Staphylococcus aureus*, a common pathogen. He then infected mice with lethal levels of *S. aureus* and injected some of them with doses of his selected rings. The control mice died whereas those that received the rings survived. The rings worked in less than an hour. (New Scientist No. 2267, 24-27, 2nd December 2000)

Magnetically tagged dendrimers used to track stem cells. Dendrimers are molecular assemblies that measure between two and 20 nanometres across, and are a star-shaped. The tips of the branches can be modified to carry reactive chemical groups, or be linked to antibodies, to pieces of DNA, or to metal atoms. Using magnetic-resonance imaging to detect the iron oxide in the dendrimer, the researchers were able to track the locations of the cells transplanted into the brains of living rats and watch as the cells made new tissue in the brain. (The Economist, Dec 20th 2001)
This illustrates how nanotechnology developments will make it possible to understand biological processes at cell-level, on which all food production ultimately depends.

Carbon nanotubes, rolled up sheets of graphite one carbon atom thick, have a wide range of novel uses. (Special issue on carbon nanotubes, Physics World, June 2000). Nanotubes are already finding applications, the latest is in detecting toxic gases such as nitrogen dioxide and ammonia, which may lead to the development of a new generation of tiny environmental sensors, "Opportunities for Industry in the application of nanotechnology" by O. Saxl, June 1999. Materials page of Foresight website www.foresight.gov.uk)

Molecular saws that kill bacteria. Scientists at MIT and Tufts University have carbon chains a few hundred atoms long. These form tiny saws, the teeth being atoms that stick out from alternate carbon atoms. In tests, short-toothed saws with points 3-6 carbon atoms long made efficient weapons against bacteria. Glass treated with these short chains killed 94% of *S. aureus*, the scourge of hospitals, and more than 99% of three other bacterial species. The saws probably kill by mechanical disruption but are not harmful to mammalian cells, which are larger than those of bacteria. (New Scientist 26 May 2001, p22)

It is also notable that two Interdisciplinary Research Centres in nanotechnology have been announced in Jun 2001, to be funded jointly by EPSRC, BBSRC and MRC and the MoD. They are to be led by Cambridge and Oxford Universities.

What are the needs of the food industry to which nanotechnology could realistically contribute?

Many of the developments and possibilities, whilst not actually being developed for the food industries, will have an impact on them. Some impacts are direct, e.g. sensors that detect pesticide residues and are cheap and simple enough for consumers to use, and some indirect, e.g. individuals having access to their own DNA profile and demanding nutrition in some way appropriate to that profile, to prevent disease, improve lifespan and health.

The following list attempts to capture the current needs of the food industry to which nanotechnology may be relevant.

Information – (meaningful, current, easily available to the appropriate people)
about the materials and products and equipment throughout the chain. Central to this are **sensors** for current situation. Even if the sensor simply determines the presence of some substance by a 'pass-fail' assessment, the next issue is **how to make use of the information**? The industry needs means of predicting the responses of food animals and plants, and their products, to every aspect of the production process.

Materials
With food safety in mind, surfaces that are inherently cleaner would be beneficial - non-scratch, self-repairing, resistant to corrosion, easy to clean, "smart" (that sense something and act in some appropriate way).

Improved materials would allow less equipment downtime via sharper, longer lasting cutting edges, lower surface wear, materials and components that indicate they are close to the end of their life, or that self-repair.

Flexibility
Versatile equipment
Versatile but smaller, workforce

Longer product shelf-life - cleaner ingredients, processes and products, better packaging, with sensors built-in

Uniformity, availability
Ingredients that are more uniform in their attributes and predictable in their performance, available all the time

Less waste and better methods for treating it

Biosecurity - food supplies safe from biological threats

Consumer confidence
part of which relies on **Traceability,** part on the ability of consumers to determine for themselves the qualities of foods.

Which nanotechnology developments are already underway, and where is development needed?

Because nanotechnology is largely still at the research stage, the costs of any products of the research are high. Initial targets for developments from the research are therefore in sectors that can bear high costs, e.g. medical, military. The food chain industries are not such a sector. So, in the first phase of nanotechnological developments, only specialised devices that have been developed for other applications and are more affordable will find an application in the food industries. However as the technology gathers pace, costs will come down and the uptake of nanotech developments within the food chain industries, and many other industries, will become attractive.

Looking ahead, it is clear that if the development of nanotechnology continues, it will have increasing impact. But what is a useful timescale over which to take a forward look? If ever achieved, the more futuristic predictions for nanotechnology will profoundly affect the lives of everyone. But the timescale and likelihood are too speculative, the implications are far wider than the food industries, Futurologists have written about how such future visions may develop. For example, the possibility of manufacturing usefully large amounts of materials by molecular assembly "bottom-up" methods. This might mean being able to manufacture materials, including food by a device like a "Star Trek rations replicator", and at reasonable cost from any ingredient containing the appropriate atoms. Such technology would clearly influence many human activities. Equally, other developments can be taken as highly likely and will have an impact, though again not specific to food industries. For example, display screens or surfaces that are large, thin and flexible and use low power.

The key questions concern the developments that are (a) perhaps only 5-10 years away, and (b) that will have a major impact on the food industries, positive or negative. Depending on the foreseen development, there may be opportunities to stimulate developments to accelerate it or enhance its benefit, or to develop strategies to mitigate developments. Following the above reasoning, the timescale adopted here is a 5-10 year one.

In the author's view, there are three areas where impact of nanotechnology is likely to have a major impact on the food industries within a 5-10 year timescale; **sensors, health in relation to food,** and **materials**. The author has reached this view having reviewed the publications listed in the bibliography, material on websites and held discussions and a brainstorm with colleagues.

1. Sensors

? Sensors is a topic where the influence of nanotechnology on the food chain industries is likely to be direct i.e. the development of a sensor and a system in which it can be used depends on developments in nanotechnology.
? The drive to measure the presence and level of many substances will produce developments in sensing technologies. The drivers are to enable better decisions to be made (by companies and consumers), processes optimised, data specific to individual items and events recorded. Once something becomes measurable, perhaps by "lab-on-a-chip" methods, legislation may be passed to control it. If the presence of e.g. a known toxin in food is detectable to a lower level, pressure will increase to enforce a more stringent limit. This would have repercussions throughout the production chain.
? The marginal cost of the working element of a sensor device is not inherently high. If specific and sensitive sensing techologies for high value applications have already been pioneered using a new nanotech method, other similar sensors based on the same principle could be cheap, even if they are technically advanced and not made in large quantities, because the development costs have been partly covered. If appropriate to, for example, the automotive industry, take-up of sensors in that sector will drive costs down, and potentially putting sensors within reach of consumers.
? There is a large number of applications for new sensors, not just one. Examples:- the presence and quantity of micro-organisms (specific species and in total), gases, volatile compounds, flavours, odours, toxins, trace elements, environmental pollutants in air and water, metabolites in plants and plant materials (e.g. proteins, sugars, oils, carbohydrates), of metabolites in animals and animal products, of authentication, genetic characters, human physiological conditions, and to measure these as appropriate in water, air, ingredient, or in the organism.
? As a vision, a 'smart' label, incorporating perhaps several sensors, on a fruit or a piece of meat could measure the current nutritional status and other quality measures, inform the consumer and/or a monitoring system if a quality problem arose, and also give information to the consumer about that particular product, its environmental credentials, source, predicted life, microbiological status, genetic information, and (see next topic) its health-enhancing nutritional values, etc.
? Sensors have to be seen as part of a complete system, and interfacing a sensor with the material being sampled may be even more challenging if the target substance is very dilute.

2. Health and Food

? The impact of nanotechnology via this topic is less direct, in that it is *via* the increasing concern of consumers about their food as the effects of food/ diet on health. The suppositions of increasing consumer concern and of logical choice based on information are not, of course, undisputed.
? Developments in nanobiotechnology and biological sciences arising from genetic decoding of organisms will lead to an improved understanding of the working of the human body and of other organisms, from bacteria to dairy cows. Diseases will be better controlled and the <u>potential</u> for a longer healthy human lifespan will be within sight. Monitoring of personal physiological status may be routine.
? The links will become much clearer between human diet and good health and/or susceptibility to disease. The influence of individual's personal genetic makeup will also become clearer, and food demands may change rapidly as people, and especially parents for their children, seek food that they expect to give health benefits.
? Individuals will become even more concerned about the presence in their food of desirable or undesirable substances, from chemicals to toxins to trace elements, and desirability of certain others. The boundary between food, functional food and pharmaceuticals will become less clear. Through developments in sensor technology already described, concerned consumers will have individual access to means of verifying many aspects of the "quality" of their food.
? Also deriving from advances in nanobiotechnology will come better understanding of microorganisms, of their beneficial as well as harmful influences, and new means of controlling specific organisms.

3. Materials

? The availability of new material properties will benefit many industries, including the food industries. Though likely to be developed for and applied first in medical, military and other high cost and critical applications they will, once the cost has fallen sufficiently, find applications in the food chain industries.
? Food industries rely on materials such as stainless steel and polymers to make possible the effective cleaning of equipment, without corrosion, ranging from from preparation surfaces to complex machinery. Nanotechnology is expected to lead to materials that have anti-bacterial properties, perhaps specific to certain bacteria only, to avoid harming beneficial ones. Such

materials may have improved surface finishes that are (a) very hard and resistant to scratching and corrosion to reduce the available sites in which bacteria can persist, (b) reduce the ability of microorganisms to attach themselves, directly or *via* biofilm formation, (c) 'smart' surfaces that can indicate the presence of organisms by signalling, or (d) are able to self-repair to eliminate scratches in which bacteria can survive.

? Ultra-hard coatings or nano-structured materials that are inherently harder but not more brittle will make possible more efficient processing machinery with extra sharp but durable cutting edges and components that wear less quickly. Components may be able to 'indicate' by some means when they are close to the end of their life, or self-repair may be possible.

? Packaging will continue to develop. The packaging of fresh foods with 'smart' materials - materials that both actively sense and respond to the surrounding and internal environment – will help keep them closer to ideal environment, and have new functions such as determining (*via* sensor elements) and displaying the status of the food, communicating information about the product to and from a central system, even in the consumer's home, and enhancing quality *via* substances released by the packaging, e.g. the contents may be the product of plant development in which the final stages of ripening are controlled via the pack by the consumer, to suit their preferences. "Smart materials" will be cheap enough to use for growing and packaging.

Suggested research needs

If nanotechnology fulfils the promise that many consider it holds, its impact on the food chain industries is likely to be significant. Of the three topics suggested as the most likely to generate impact within the timescale of 10 years, that of Sensors is likely to have the most *direct* impact, *i.e.* nanotechnological developments in this topic will lead directly to technology that changes the food chain industries. In the other two topics, Health and Food, and Materials, nanotechnology will have impact less directly, in that nano- and other technologies will enable developments in medical and materials science that will impact on many industries, of which the food chain industry will be one. Health and Food is a very general topic and the most difficult to be specific about because of the influence of consumer choice. Given that very little research in nanotechnology is being pursued with the food industries as the target, there will be a need to monitor nanotechnological research and development so as to recognise at an early stage advances relevant to the needs of the food chain industries. In some cases the activity may require further nanotechnology research, but there will also be a need for systems that exploit developments in nanotechnology in a food context.

It is suggested that

1. ***There is a need for continuing scanning of the nanotechnology horizon, with a particular need in the topics of Sensors and Materials, to evaluate nanotechnological research and development in relation to DEFRA's aims and objectives. This would aim to identify needs for further research and development that would enable exploitation for the benefit of the industries that DEFRA serves.***

2. ***Two such needs, appropriate to the food chain industries, are***
   (a) systems to exploit nanotechnological developments in sensors, and
   (b) exploitation of material surfaces that are fundamentally less hospitable to bacteria important in food hygiene

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Note: Because many of the sources below overlap in their scope, they are not referenced individually in the text of the report. In many cases material from the source was not directly used in the report, but all of the sources were considered relevant.

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