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Review

Nanotechnologies in the food industry – Recent developments, risks and regulation

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Recent research has highlighted the potential for nanotechnologies' use in wide ranging food applications, including improving supplements, novel food packaging, increasing the range of food textures, colours and tastes, increasing the efficiency of liquid filters, cooking oil catalysation and targeted crop pesticides. Because of these new developments it is likely that radical changes in the way food is perceived, stored, packaged, transported, monitored, consumed and processed will come about. Available literature suggests that many uncertainties remain about nanomaterials, including the potential for bioaccumulation and potential human health risks. While proposed applications of nanotechnologies are wide and varied, developments are met with some caution, while progress may be stifled by lack of governance and potential risks.

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Introduction

The food and beverage sector is a global multi trillion dollar industry. All the major food companies are consistently looking for ways to improve production efficiency, food safety and food characteristics. Extensive research and development projects are ongoing with the ultimate goal of gaining competitive advantage and market share. For an industry where competition is intense and innovation is vital, nanotechnologies have emerged as a potential aid to advances in the production of improved quality food with functionalised properties. Advances in areas such as electronics, computing, data storage, communication and the growing use of integrated devices are likely to indirectly impact the food industry in the areas of food safety, authenticity and waste reduction.

According to the National Nanotechnology Initiative (2009), in the United States the federal funding budgeted for $1.64 billion to be spent on the advancement of nanotechnologies in 2010. This represents steady growth in the area (up from $1.5 billion in 2009). This will be divided out among eight investment categories, none of which is specifically food; it can be said, however, that the food industry is likely to benefit hugely from funding to other areas, such as "nanomaterials".

Nanotechnologies involve the manipulation of matter at a very small scale – generally between 1 and 100 nanometres. They exploit novel properties and functions that occur in matter at this scale. Nanomaterials and nanoparticles may include any of the following nano forms: nanoparticles, nanotubes, fullerenes, nanofibres, nanowhiskers, nanosheets. A nanoparticle is defined as a discrete entity that has three dimensions of the order of 100 nm or less (Som *et al.*, 2010). There is no scientific reason in support of this specific upper limit. A nanomaterial is defined as an "insoluble or biopersistent and intentionally manufactured material with one or more external dimensions, or an internal structure, on the scale from 1 to 100 nanometres" as detailed in the recent EC Cosmetics Regulation ((EC) No 1223/2009). Efforts are underway to establish a more comprehensive definition for nanomaterials. Hence, this is a provisional definition until a uniform, European and international definition is made available (Mildau & Huber, 2010).

Nanotubes have a cylindrical lattice arrangement of material; fullerenes have a spherical molecular arrangement; and nanofibres have a length to diameter ratio of at least 3:1 and are in the nano range (Hoet, Bruske-Hohlfeld, &

Salata, 2004; O'Brien & Cummins, 2008). Nanowhiskers are fine fibres in the nano range; they are 5–20 nm in cross-section with lengths of several micrometres (Pandey, Lee, Chu, Kim, & Ahn, 2008). Nanosheets are an arrangement of material where only one dimension is in the nano range (Kumar, Depan, Singh Tomer, & Singh, 2009). Many of these different nano forms are either in use or under investigation for use within the food industry. This review refers to a selection of these which best represents the developments in the food industry.

Many common elements and compounds behave differently at the molecular and atomic scales of nanotechnology than they do at larger particle sizes. When discussing properties which change with decreasing size, it is important to distinguish between properties that change smoothly over a series of size reductions and properties that change abruptly below a certain critical size. The abrupt change of properties below a certain size is the key novelty of nanotechnologies. This critical size depends on the property in question and on the material, hence the difficulty with defining an upper size range.

Although there are many benefits of these technologies there is also concern over potential negative effects. In the case of particulate nanomaterials coming into contact with the human body by design or by accident, for example, the reduction in particle size associated with nanotechnologies potentially reduces the effectiveness of barriers to the penetration of foreign materials into the human body and to their movement within the body. There is growing concern that the use of nanomaterials in the food industry could result in particulate nanomaterials gaining access to tissues in the human body, resulting in accumulation of toxic contaminants and therefore adversely affecting human health (Chau *et al*., 2007).

Many new consumer products containing nanoparticles have been launched to the market and are beginning to impact on the food associated industries (Bouwmeester *et al*., 2009; Chaudhry *et al*., 2008). Table 1 provides a non-exhaustive list of current uses of nanotechnologies in the food industry. It is clear from the table that the use of nanoscale silver (Ag) as an antimicrobial is common amongst the available products/proposed products/research topics of this area. Other nanomaterials used include zinc oxide (ZnO), used for light activated sterilisation of surfaces (Li, Xing, Jiang, Ding, & Li, 2009) (at research stage) and the size reduction of starch particles to the nano range in order to increase the efficiency of an adhesive (commercially available). Note that this table is limited to information available in English.

Nanotechnologies are set to impact on the food industry at all stages of production from primary production at farming level, due to advances in pesticide efficacy and delivery (novel formulations and better crop adherence) (Silva *et al*., in press), to processing where emulsion creation and encapsulation have progressed to the nanoscale (Donsì *et al*., in press; Rao & McClements, 2011). The area of food packaging has seen much innovation in barrier improvement with the use of various nanoscale fillers and this has also resulted in reduced effects of targeted accelerating factors of spoilage and contamination. Intelligent packaging is the new generation of packaging, many of which are in the late development stages, which incorporates sensors and sometimes nanosensors. They can communicate information about the food to the consumer or react to the information and change conditions within the packaging to delay spoilage/contamination (Neethirajan & Jayas, 2011).

As with many new technologies, being enthusiastic in the rush to market, nanotechnologies may distract from the importance of the investigation of possible health and environmental implications (Morgan, 2005). The scientific community must learn from previous introductions of new technologies, being particularly sensitive in the food area. For example, genetically modified foods were not well received by consumers because there was a perceived risk associated with them. Thorough risk assessment of nanotechnologies in the food sector should provide a sound foundation on which commercial products can be launched with confidence, or withdrawn to protect consumers and the environment from potential hazards (O'Brien & Cummins, 2010a, 2011).

The focus of this review is recent developments in nanotechnologies in the food sector, both in terms of the food matrix and also in food-related industries such as food packaging. The manufacture of nanomaterials, their uses, applicable legislation and associated risks are also discussed.

Manufacture of nanomaterials

'Top down' and 'bottom up' are the terms given to the two main categories of nanomaterial manufacture. Top down manufacturing of nanomaterials involves breaking down larger particles of matter to particles of only nanometers in dimension by physical or chemical means. An example of a mechanism used to produce such nanomaterials is mechanical milling. Dry milling of wheat bran has potential as a bioactive food ingredient, but is not widely used at present. Zhu, Huang, Peng, Qian, and Zhou (2010) cites the polymer nature and inadequate equipment development as the reasons for the lack of uptake of this technology. The antioxidant effect of green tea has also been improved by using this size reduction technology (Shibata, 2002). Homogenisation is also a top down size reduction mechanism. It is a well established industrial process which uses pressure to reduce the size of fat globules. It is used globally in the dairy industry. The use of lasers and vaporisation followed by cooling are other top down methods of nanomaterial manufacture reported by Brody, Bugusu, Han, Koelsch Sand, and McHugh (2008). Bottom up manufacturing is the alternative production method of nanomaterials. Methods of bottom up manufacture include crystallisation, layer-by-layer deposition, solvent extraction/evaporation, self-assembly, microbial synthesis and biomass reactions (Brody *et al*., 2008). This approach is capable of producing more complex molecular structures by design based on self organisation of biological compounds.

Table 1. Nanotechnologies in the food industry.

	Product	Nanocomponent	Function of nanocomponent	Commercial status	Further information	Reference
Metallic nanoparticle	BlueMoonGoods™ Fresh Box Silver Nanoparticle Food Storage Containers	Ag nanoparticles	Antimicrobial	Withdrawn from website	Nanoparticles permanently embedded in the container	(Alfadul & Elneshwy, 2010).
	Nano Care Technology, Ltd. Antibacterial Kitchenware	Ag nanoparticles	Antimicrobial	URL no longer available		(Bouwmeester *et al.*, 2007)
	Sunriver Industrial nanosilver fresh food bag	Ag nanoparticles	Antimicrobial	Commercially available	Ag has been shown to migrate from these bags	(Huang *et al.*, 2011)
	FresherLonger™ Plastic Storage Bags	Ag nanoparticles	Antimicrobial	Commercially available but antimicrobial and Ag nanoparticles have been removed from the description	Resealable zip lock	(Bouwmeester *et al.*, 2007)
	SongSing Nano Technology Co., Ltd. Nano Plastic Wrap	ZnO	Anti-UV, reflecting IR., sterilising and anti-mold, better temperature tolerance, fire-proof	Withdrawn from website	ZnO uses light to sterilise the surface of the film and therefore, the food.	(Bouwmeester *et al.*, 2007)
Complex nanoscale structures	Fluorescent nanoparticle probe	Silica	Detection of *Salmonella*	At research stage		(Wang, Xu, Wu, Ye, & Yang, 2011)
	Oilfresh Nanoceramic inserts for deep fat fryers	Not disclosed	Catalytically inhibits the clumping together (polymerisation) of the frying oil that is induced my heating	Commercially available	This product has been authorised by the FDA in the US and NSF Int'l.	(Farhang, 2007)
Incorporated active nanomaterials	Radio Frequency Identification: Handheld device	Not disclosed	Monitoring storage conditions detection of contaminants etc.	At research stage		(Nachay, 2007)
	Research into TiO_2 incorporated into polymer matrices	TiO_2 10 −15 nm	O_2 scavenging	At research stage		(Xiao-e *et al.*, 2004)
Filters with nanopores	Saehan Industries Korea Nanofiltration membrane	-	Desalination of water	Currently undergoing tests in the USA		Qin, Oo, and Kekre (2007)
Nanosized nutrients/foods	RBC Life Sciences®, Inc. Nanoceuticals™ Slim Shake Chocolate	Not disclosed	Claimed enhanced uptake, designed to carry nutrition into cells	URL no longer available		(Bouwmeester *et al.*, 2007)
	Unilever is researching a reduced fat ice cream.	Not disclosed	Product design compensates for the loss in creaminess due to fat reduction	At research stage. May be commercially available but no nano claim has been made	Uniform sized emulsion	(Neethirajan & Jayas, 2011)
Delivery systems (nanoencapsulates)	Karate ZEON Controlled release of active component lambda cyhalothrin	Not disclosed	Insecticide used on food crops	Commercially available	Increased efficacy, water solubility, crop adherence, triggered release	(Bouwmeester *et al.*, 2007)

Non-metallic nanomaterials	Bayer Durethan KU 2601 packaging film	1 nm × 1 μm Silicate platelets	Improved O_2 barrier and improved gloss	Commercially available	Used for O_2 sensitive foods. Mixes silicate nanoparticles with polyamide precursor prior to polymerisation	(Alexandre & Dubois, 2000)
	Ecosynthetix Adhesive for burger containers	50–150 nm Starch nanospheres	Lower heat activation temperatures, less water required for wetting and reduced drying times compared to traditional adhesives	Commercially available	Used in the fast food chain McDonalds	(Das, Saxena, & Dwivedi, 2009)

It involves arranging molecules step by step to design the particles so that they have specific features. An example of the self-assembly of biological entities which results in a stable nanomaterial is the casein micelle (Sozer & Kokini, 2009).

Current and projected applications of nanotechnologies in the food sector

Nanotechnology derived food ingredients

Organic constituents that are naturally present in foods such as protein, carbohydrate and fat can vary in size from large polymers to simpler molecules in the nano range. Organic nanomaterials can be synthesised for specific purposes such as the encapsulation of nutrients to increase bioavailability, enhance taste, texture and consistency of foodstuffs or mask an undesirable taste or odour. Functionalities of such nanomaterials (e.g., particle size, size distribution, potential agglomeration and surface charge) can be affected by the biological matrix in which they are held (Powers *et al*., 2006) such as the composition of a food. The science of the production of nano-derived food ingredients is still in its infancy; nevertheless, it shows much promise with the prospect of improving product functionality without compromising product quality or safety.

Emulsion stability

The use of nanoemulsions is an example of how a nanotechnology can be applied to an existing process which can prove beneficial for the food industry. The small droplet size gives nanoemulsions unique rheological and textural properties which render them transparent and pleasant to the touch (Sonneville-Aubrun, Simonnet, & L'Alloret, 2004); both of these unique features can be desirable in the food industry and the cosmetics industry. Using nanoemulsions in food products can facilitate the use of less fat without a compromise in creaminess, thus offering the consumer a healthier option. Products of this type include low fat nanostructured mayonnaise, spreads and ice creams (Chaudhry *et al*., 2008): the latter has an expected fat reduction from 8–16% to 1% (Hall, 2005). A 2.5% fat ice cream is commercially available worldwide from a recognised premium ice cream brand which claims to have no flavour defects due to the low fat content, however no nanotechnology claim is made by the product. More choice of such low fat ice cream is available in the United States where many brands have introduced them. As the size of the droplets in an emulsion is reduced, the less likely the emulsion will break down and separate. In this way nanoemulsification may reduce the need for certain stabilisers in a product. Nanoemulsions look set to play a future role in revolutionising the production of spreads and mayonnaise, but this is very much still in development stages.

Nutraceuticals at the nanoscale

Nutraceutical compounds such as bioactive proteins are used in functional foods to impart a health benefit to

consumers in addition to the nutrition that the food itself offers. Nanomaterials can be used as bioactives in functional foods (Chau *et al*., 2007). Reducing the particle size of bioactives may improve the availability, delivery properties and solubility of the bioactives and thus their biological activity because the biological activity of a substance depends on its ability to be transferred across intestinal membranes into the blood (Chen, Weiss, & Shahidi, 2006; Shegokar & Müller, 2010). In addition, nanotechnologies can be utilised to improve the stability of such micronutrients during processing, storage and distribution (Chen *et al*., 2006). Commercial success in this area has been achieved by Omega-3 fatty acids, and certain beneficial probiotic bacteria species, lycopene, Vitamin D_2 and *beta*-Carotene have demonstrated potential commercial success in research studies (Neethirajan & Jayas, 2011). Maintaining nutraceuticals in a stable state throughout the production process is invariably challenging. The prospect of the production of nutraceuticals at the nanoscale, which will have increased stability throughout the processing chain, will be of significant interest to food processors trying to maximise nutrient content and hence will ultimately be of benefit to consumers.

Nanoencapsulation

In recent years the role of food materials has evolved from being solely a source of nutrients to contributing to the health of consumers. When certain nutrients are immobilised in different tailored carriers, the nutrients, such as enzymes, can be resistant to proteases and other denaturing compounds and can have improved stability to pH and temperature changes. Microencapsulation of foods is well established: microencapsulated fish oil has been added to bread for health benefits. The microencapsulating process masks the unpleasant taste of fish oil (Chaudhry *et al*., 2008) and this bread is currently commercially available. The nanoencapsulation of food ingredients and additives is a logical progression of the technology to provide protective barriers, flavour and taste masking, increased bioavailability, increased potency, controlled release and better dispersion in aqueous systems for water-insoluble food ingredients and additives (Chaudhry *et al*., 2008; Mozafari *et al*., 2006).

The major protein found in corn, zein, has received attention in food nanotechnologies. Zein nanomaterials have the potential to form a tubular network resistant to microorganisms (Sozer & Kokini, 2009). The use of zein nanomaterial as a vehicle for flavour compounds and the nanoencapsulation of dietary supplements has been explored (Sozer & Kokini, 2009).

A nanotube is a wire-like structure most frequently composed of carbon. Nanotubes of α-lactalbumin have a cavity diameter of 8 nm which may enable the binding of food components such as vitamins or enzymes (Srinivas *et al*., 2010). These cavities could also be used to encapsulate nutraceuticals or to mask undesirable flavour/aroma compounds (Graveland-Bikker & de Kruif, 2006). Nanotubes can be obtained from milk protein. Given appropriate conditions of partial hydrolysis of milk with a specific protease, α-lactalbumin will self assemble into nanotubes (Graveland-Bikker & de Kruif, 2006). Because the origin of these nanotubes is milk protein or in the case of zein, corn protein, they are considered to be food grade and so their introduction to the market should be relatively easy for a nano ingredient. The food grade association of these proteins may facilitate widespread applications in nanoencapsulating nutrients, supplements and pharmaceuticals.

Colour effects of nanotechnologies

Nanotechnologies in relation to food colour are not well researched. However, the use of the oil-soluble pigment compound β-carotene to colour aqueous based foods may now become possible using nanoemulsion technology (Astete, Sabliov, Watanabe, & Biris, 2009). The formation of nanosized structures using alginic acid and calcium ions may allow the natural fat-soluble colourant to be used in a novel way. An advantage of this method would be that the colour of a food system could be changed from yellow to dark orange by altering the concentration of β-carotene in the nanostructures. A patent has been filed on this method but no products have claimed the utilisation of this particular colour enhancement and so it can be considered that the idea is still being developed.

Food packaging

Packaging of the future is likely to be more than just a physical container that provides food with protection from the surrounding environment. Further subdivision of nanopackaging is required; packaging from which migration into the food is purposeful and intended and packaging from which no nanoparticles migrate (in any significant amount). The former is likely to be subjected to greater safety assessments and negative consumer perceptions and for these reasons is less likely to advance as quickly as the latter. Using nanotechnologies to improve packaging materials is likely to be very costly and will not be introduced until methods are optimised, results are consistent and prove to weigh up favourably against costs.

Nanocomposites

According to Yang, Wang, and Wang (2007), there are two main approaches to produce polymer nanomaterials. The first is to manufacture polymer materials at a nanoscale; the alternative, most popular and most relevant to this review is to introduce particulate nanomaterials into a polymer matrix to achieve a nanocomposite. Food contact materials (FCMs) have been developed with improved flexibility, gas barrier properties, temperature control and moisture stability due to the inclusion of nanoscale fillers. The filler can reinforce the polymer matrix. The use of nanoscale fillers in composite films represents a radical, promising alternative to conventional polymer composites (Alexandre & Dubois, 2000; Giannelis, 1996; Sinha Ray, Yamada, Okamoto, & Ueda, 2002). This new generation

of composites have significant improvements at low filler rates (generally lower than 5%). Improvements in modulus, dimensional stability and solvent or gas resistance can be seen when compared to conventional polymers. They bring no significant change in density, transparency or flow of the film and they may enhance surface properties and recyclability (Sorrentino, Gorrasi, & Vittoria, 2007).

Gas barrier properties of composites can be greatly improved with the inclusion of particulate nanomaterials. The gas travelling through the larger polymer particle matrix which includes a nanoscale filler must travel a more tortuous path than gas travelling through the conventional polymer matrix without the filler. Among the nanoscale fillers used in the production of nanocomposites is the clay montmorillonite. It consists of stacked silicate sheets with a high ratio of length to thickness (aspect ratio) and a plate-like morphology. Montmorillonite has been widely studied and is of particular interest due to the successful incorporation into composite materials and the advantageous properties which the reinforced films exhibit which are attributed to this high aspect ratio (Rhim & Ng, 2007). Laponite is another filler suitable for polymers undergoing research for its inclusion in nanocomposites. It has a higher aspect ratio than montmorillonite (Chung *et al*., 2010). Aspect ratio can be a determining factor for the efficacy of a nanoparticulate filler (see Fig. 1). This is due to the lengthening of the path of diffusion of a gas caused by weaving around the obstructive filler particles, thus retarding gas exchange through the packaging material (Adame & Beall, 2009; de Azeredo, 2009; Sinha Ray & Okamoto, 2003).

Bionanocomposites use biodegradable materials and incorporate nanomaterial fillers to minimise the disadvantages of not using traditional packaging materials (Sorrentino *et al*., 2007). Not only do they protect the food which they surround and prolong its shelf life with the aid of nanofillers, but the use of nanocomposites reduces the use of plastics as packaging materials, require less fossil fuel in production and biodegrade, making them more environmentally friendly (Sozer & Kokini, 2009).

Active and intelligent FCMs

Food packaging materials that are capable of releasing nanoscale antimicrobial compounds, antioxidants and/or flavours which would improve the shelf life or sensory characteristics of a food are termed "active". Active packaging seems to be a logical follow on from nanofiller technology and intelligent packaging, a type of active packaging, seems to be where research has a new found focus. The incorporation of active compounds into food packaging materials where they are bound rather than designed to migrate are more common than packaging designed to release particulate nanomaterials into foods. The latter will be considered as food additives under regulation. The substance will need to have all the required safety data to ensure their place on the food additives' positive list before their use. FCM-bound active particulate nanomaterials are being used in commercial products such as commercially available nano-Ag embedded baby bottles. These impart an active effect but are not ingested with the food (Alfadul & Elneshwy, 2010). In theory, compared to FCMs which have intended release of nanoparticulate nanomaterials, FCMs which bind particulate nanomaterials may have a marginal "active" effect limited only to the FCM surface.

Research into active FCMs is paving the way for intelligent FCMs. Nanosensors can be incorporated into food packaging matrices which have the ability to identify specific microbial and/or chemical contaminants or environmental conditions. These can respond in a way that alerts the consumer to the contamination (Neethirajan & Jayas, 2011). This technology is also capable of changing an environment in response to a stimulus. Stimuli may include a specific pH or pressure, or the presence of gasses, liquids or products of microbial metabolism or spoilage accelerators such as temperature or light intensity (Otles & Yalcin, 2008). From scientific literature it appears that most of these are at development stages. Due to current EU legislation it is not likely that they are commercially available in the EU, particularly those types of intelligent FCMs that respond to contamination in a way that releases a substance into the environment of the food to counteract the contamination. These are discussed further by Pereira de Abreu *et al*. (2011).

Antimicrobial nanopackaging (active)

The combination of food packaging materials and active substances is a new way to control surface microbial contamination of foods. Some nanomaterials exhibit antimicrobial effects. For such active packaging materials, sharing a common interface or physical contact with the food surface is essential (Vermeiren, Devlieghere, & Debevere,

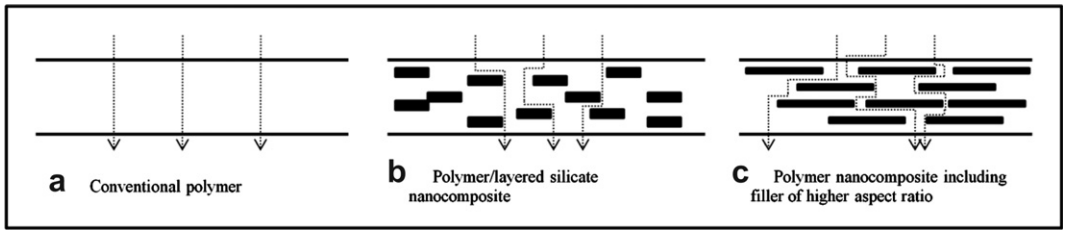

Fig. 1. Schematic illustration of formation of tortuous path created by the use of nanosized fillers in nanocomposites effectively lengthening the path of diffusion through the polymer matrix. Adapted from (Adame & Beall, 2009; de Azeredo, 2009; Sinha Ray & Okamoto, 2003).

Table 2. Nanopackaging: research and commercial applications.

% Nanomaterial	Nanomaterial	Author	Food type	Size shape	Packaging matrix	Method	Function nanomaterial/ film
4	Montmorillonite (mmt)	(Avella *et al.*, 2005)	Lettuce, spinach	–	Potato starch, potato starch/degradable polyester	–	–
5	mmt	(Rhim, Hong, Park, & Ng, 2006)	Non food system media: tryptic soy broth (TSB), brain heart infusions (BHI)	–	Chitosan/acetic acid	–	Antimicrobial activity (AA)
5	Organically modified mmt	(Rhim *et al.*, 2006)	TSB and BHI	–	–	–	AA
5	Ag nanoparticles	(Rhim *et al.*, 2006)	TSB and BHI	76.8 ± 10 nm	–	–	AA
5	Ag nanoparticles	(Rhim *et al.*, 2006)	TSB and BHI	76.8 ± 10 nm	–	–	AA
20	Ag zeolite (Aglon)	(Rhim *et al.*, 2006)	TSB and BHI	<5.0 μm	–	–	AA
–	Titanium dioxide (TiO_2)	(Chawengkijwanich & Hayata, 2008)	lettuce	7 nm	Polypropylene	Manually coated	AA
–	Ag containing polyethylenoxide	(Nobile *et al.*, 2004)	Apple juice	90 nm	Polyethylene	–	AA
–	silicate	(Alexandre & Dubois, 2000) commercial name Durethan KU 2601	O_2 sensitive food eg: orange juice	1 nm × 1 μm platelets	Polyamide	Mixing prior to polymerisation	O_2 barrier and improved gloss
1	mmt	(Chung *et al.*, 2010)	–	–	Cornstarch	–	Improved modulus and strength (IM&S)
5	mmt	(Chung *et al.*, 2010)	–	–	Cornstarch	–	IM&S
7	mmt	(Chung *et al.*, 2010)	–	–	Cornstarch	–	IM&S
–	laponite	(Chung *et al.*, 2010)	–	20–30 nm × 1 nm	Cornstarch	–	IM&S
–	Chitosan modified mmt	(Chung *et al.*, 2010)	–	–	Cornstarch	–	IM&S
–	Multi walled carbon nanotube based sensor	(Nachay, 2007)	–	–	Ultra thin polymer substrates	–	Food borne pathogens, temperature and moisture level.
5	Nanoter™ (organophillic surface modified kaolinite)	(Sanchez-Garcia *et al.*, 2007)	–	3 μm	PET	Melt blending	Improve O_2 barrier and decreased water permeability
1	Nanoter™ (organophillic surface modified kaolinite)	(Sanchez-Garcia *et al.*, 2007)	–	3 μm	PET	Melt blending	Improve O_2 barrier and decreased water permeability
12.5	Titania (TiO_2)	(Xiao-e *et al.*, 2004)	–	10–15 nm	Polyethylene oxide (PEO), polyethylene glycol (PEG) and polyvinyl chloride (PVC)	Sonic horn dispersion, followed by concentration step. Doctor blade method of film casting	O_2 scavenging
0.25	ZnO	Emamifar, Kadivar, Shahedi, and Soleimanian-Zad (2011)	Orange juice	70 nm	Hexagonal	Melt mixing in twin screw extruder	AA against *Lactobacillus plantarum*
1	ZnO	Emamifar *et al.* (2011)	Orange juice	70 nm	Hexagonal	Melt mixing in twin screw extruder	AA against *Lactobacillus plantarum*

2002). These active FCMs can extend the product shelf life, enhancing food quality and safety and ultimately leading to less food waste.

Time temperature logs (intelligent)

Time temperature logs have the potential to assist in product biosecurity and traceability. When an expiry date is assigned to a product, it is under the assumption that the product will be kept within certain environmental conditions (temperature, O_2 concentration, humidity etc.); however these conditions are not always maintained throughout distribution. Deviations from the recommended storage conditions could lead to the premature deterioration of the food and may even cause harm to the consumer due to the presence of toxins or pathogens. When integrated into food packaging, nanosensors can detect specific indicators of pathogen metabolism or can alert or inform the consumer about a product's temperature, light or O_2 exposure (tampering) history. This could eliminate the need for expiry dates in some incidences and may even give the consumer a more accurate estimation of the state of spoilage of the food. For manufacturers it is a way of protecting against malhandling of a product following dispatch, ensuring the product reaches the consumer in a suitable state. Nachay (2007) has reported that nanosensors are already under development and that they have been commercialised. The use of sensors of this kind is not yet widespread throughout Europe due to high costs and low uptake from retailers and food production companies. Legislative restrictions may apply if chemicals used in the sensors (dyes etc.) are not permitted for use within FCMs.

Nanopackaging effects on foods

The effect a nanopackaging has on a food depends on its active ingredient, namely the composition of the nanomaterial that is involved. The polymer matrix may also have a role to play in controlling the action of the nanomaterial; for example it may influence particle release rate. Research is ongoing in this area and many concepts have developed into commercially successful products. Some of the reported benefits that have been published in recent literature have been summarised in Table 2, including the packaging matrices incorporating the various nanomaterials, percentage incorporation and size/shape of nanomaterials. (Note that this table is non-exhaustive and is limited to product information and studies available in English).

Recent studies have shown that some nanomaterials can induce cell death in eukaryotic cells (Long *et al*., 2006; Nel, Xia, Madler, & Li, 2006) and growth inhibition in prokaryotic cells due to cytotoxicity (Brayner *et al*., 2006; Thill *et al*., 2006). This has relevance in the food industry in relation to the control of spoilage microorganisms and pathogens (prokaryotic cells). One mechanism put forward theorises that cell nutrients adsorb to the large surface area of the nanomaterial which starves the cell (Geys, Nemery, & Hoet, 2010). Metal nanomaterials have received a lot of attention in this area and products utilising the unique antimicrobial properties of metals such as silver and gold have been launched on the market (Bouwmeester *et al*., 2007). Metal oxides have also been incorporated into commercialised products displaying light activated microbe inactivation (Bouwmeester *et al*., 2007).

Ag nanoparticles absorb and decompose ethylene (Hu & Fu, 2003), thus food packaging films which incorporate Ag impart this effect on the associated food. This may contribute to its positive effects on the shelf life of fruits and vegetables. It was observed in tests that the senescence of the Chinese fruit jujube was retarded by nanocomposite polyethylene film with Ag nanoparticles (Li, Li, *et al*., 2009). A coating of Ag nanomaterial has also been reported to prolong the shelf life of asparagus samples by decreasing microbial growth (An, Zhang, Wang, & Tang, 2008). This particular study is exploratory in nature; however, as applying Ag nanoparticles to the asparagus in a solution type coating as described in this study, despite being highly effective in prolonging the shelf life of the vegetable, is likely to be of public concern. Due to its activity against *Escherichia coli* TiO_2 powder-coated food packaging films are suggested for use with freshly cut produce (Chawengkijwanich & Hayata, 2008). Recent studies in the area of muscle foods include the study of antimicrobial activity of absorbent pads containing Ag nanoparticles by Fernández *et al*. (2009); the antimicrobial effect against *Escherichia coli* and *Staphylococcus aureus* was confirmed during the modified atmosphere packaging preservation of poultry meat. In another study, a xanthine amperometric sensor was developed based on calcium carbonate nanoparticles which can determine the freshness of fish samples (Shan, Wang, Xue, & Cosnier, 2009). Muscle foods are generally high value, perishable goods and because of this they are an ideal target for value nanotechnology-assisted packaging. Research into packaging for dairy products and cereal foods is currently lacking and appears to be a logical next step for the application of this technology.

Food packaging materials used in conjunction with the particulate nanomaterials

Polymer matrices used in nanocomposites include polyamides, nylons, polyolefins, ethylene-vinylacetate copolymer, polystyrene, epoxy resins, polyurethane and polyethylene terephthalate (PET) (Šimon, Chaudhry, & Bakos, 2008). The choice of polymer matrix is a major factor in the efficacy of the active components in the film. Density as a factor is particularly important as it determines the rate of release of bioactives (Cruz, Sanches Silva, Sendón García, Franz, & Paseiro Losada, 2008), which may be required to either be bound in the matrix or be released over time. It is likely that perfecting the nanoparticle size, concentration combination, as well as the factor of the release rate will take time. The shelf life of the food and the contact area between the packaging and food must also be considered. It is also possible that combining two or more

nanoparticulate components in one film would optimise a food packaging system. In this instance the inclusion of each individual nanomaterial would improve the film without affecting the effect of another nanocomponent, and may even complement one another.

Risk assessment

Potential risks to both human health and the environment may exist. The use of nanotechnologies in the food industry may present potential risks due to the use of novel materials in novel ways, thus risk assessments must be carried out to identify and quantify these risks. All applications of this new technology must be assessed for safety of use. In the EU, the Directorate General of Health and Consumer Protection has set up the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR). This committee provides opinions on questions concerning emerging or newly identified health and environmental risks on issues which require a comprehensive assessment of risks to consumer safety or public health (SCENIHR, 2010). Nanotechnologies fit this profile. SCENIHR focuses on nanotechnologies' risk assessment with particular interest in establishing recognised terminology in the field so that research can be integrated to a certain extent. Research breakthroughs in the area of potential benefits of nanotechnologies are being published at an increasing rate so risk analysis is urgently required. Maynard (2010) put forward a view that an integrated system of research is required to fully understand the implications of nanotechnologies on human health, to pre-empt adverse health effects and to proactively minimise them. In this ideal research team, risk assessors would work alongside toxicologists and food technologists among others.

In order for nanotechnologies to be used to their full potential, they must be accepted by consumers. Clear communication of the benefits of using nanotechnologies for various purposes over existing technologies must be conveyed to the public. Both benefits and risks should be acknowledged; however, for acceptance it must be clear to the public that not only do the benefits outweigh the risks, but that the risks are acceptable.

Exposure routes

Exposure to nanomaterials as a result of nanotechnologies being used in the food industry can take three main routes; dermal contact, inhalation and ingestion. Exposure to nanomaterials from any of these routes may represent a failure in a process put in place to prevent such occurrences. Alternatively, imparting nanoparticles may be the intention of the product. In other industries this type of intentional exposure to nanomaterials occurs *via* other routes; in the cosmetics industry, for example, sunscreens containing nanomaterials are designed for direct skin application. The main exposure of concern in the food industry occurs *via* ingestion (nanofoods and nano-related FCMs). Chen *et al*. (2006) has shown that the mammalian gut can absorb particulate nanomaterials. Exposure routes specific to the food industry can be categorised as follows.

The use of nanoingredients in foods and health supplements

A lot of basic food constituents can be present in a food matrix in nano form naturally: by their nature they are soluble in physiological conditions and so can be called nanoparticles but are not particulate nanomaterials. To improve the functionality and/or nutritional value of a food, food ingredients are engineered to be smaller than their traditional counterparts. Exposure to nanoparticles can occur through ingestion of food containing (engineered organic or inorganic) nanoparticles by design.

It is possible that such nanoparticles will form compounds with other food material, interact with one another, or remain in a free state while in the alimentary canal. How this will affect absorption is unknown. The increased use of such nano forms may call for the revision of the Recommended Daily Allowances (RDA) of the food ingredient. For example, the use of nanoemulsification in ice cream or mayonnaise allows for the use of significantly less fat than their traditional counterparts without the loss of mouthfeel (Chaudhry *et al*., 2008). The question remains, however, whether the fat globules in the nanoscale are more likely than the traditional, larger globules to be absorbed across the gut epithelial.

The use of nanomaterials in food packaging

It is worth noting that there may be risks to the consumer in the form of migrating particulate nanomaterials from FCMs into food. The results of this kind of exposure have not been fully determined and the lack of such data poses a major stumbling block to the assessment of risks posed by the consumption of foodstuffs in contact with nanopackaging. With this particular group of applications, it is usually not intentional that humans would be exposed to the nanomaterials used. Potential human exposure is currently based on migration test results, and predicted safe levels of exposure are based on the results of animal exposure trials. Ingestion of foods previously in contact with nanopackaging presents an exposure route due to weakness in packaging performance and subsequent transfer of particulate nanomaterials from the packaging into the food. It is not yet known whether consumption of foods containing transferred particulate nanomaterials poses a significant health risk. This will depend on the toxicity of the nanomaterial used, the rate of migration and the consumption rate of the particular food.

A model put forward by Šimon *et al*. (2008), which predicts migration and quantifies nanoparticles migrating from nanopackaging, requires information about the packaging matrix and about the nanoparticles themselves. Rate of migration of a system increases with decreasing polymer dynamic viscosity and nanoparticle size. This demonstrates the potential for migration of nanoparticulate materials from packaging materials and the necessity for quantitative risk assessment.

A migration study carried out by Avella *et al*. (2005) reported insignificant mineral increases in vegetables packaged in a nanocomposite, derived from a biopolymer with incorporated montmorillonite (nanoclay). An increase, but not sufficient to exceed the EC normative on food contact materials was observed in the amount of Silicon detected in the food samples, the main component of nanoclay. A similar rate of migration in a system using metallic nanoparticles with notable antimicrobial properties may not be as acceptable because a dose-response relationship has not yet been established for such a nanoparticle type and its affect on human health or the environment.

Supporting the view that food packaging, produced using nanotechnologies, is one of the most promising applications of nanotechnologies in the food sector, a major breakthrough for nanotechnologies occurred in November 2008: the European Food Safety Authority (EFSA) Scientific Panel on FCMs, Enzymes, Flavourings and Processing Aids (CEF) adopted a positive safety opinion that concluded that titanium nitride nanoparticles used at a level of 20 mg/kg in PET bottles did not migrate and therefore were not a toxicological risk for food (National Nanotechnology Initiative, 2009).

Commercially available food storage bags containing Ag nanoparticles were filled with four kinds of food simulating solutions to test for migration (Huang *et al*., 2011). Results indicated that migration of Ag nanoparticles from the polyethylene bags into the food simulating solutions had occurred and that the amount of migration increased with storage time and temperature. This result may impact negatively on the progress of such packaging materials.

Biodegradable packaging is a growing trend in the packaging industry due to its positive impact on the environment. The progression of this technology to incorporate nanotechnologies to produce bionanocomposites raises the issue of incidental environmental contamination as a result of nanomaterials being released following polymer degradation. Ecotoxicity tests are required to determine the risks posed by nanomaterials on the environment, results of which could be displayed in an understandable manner on packaging to enable the consumer to make an informed choice. Priority should be given to nanomaterials that are already in use in this way.

Food exposed to nanomaterials during farming practice

Nanomaterials are not currently being used in animal feed, however it is likely that the benefits of nanotechnologies maybe put to use in this sector where product performance/digestibility is important. Veterinary medicines that contain nanomaterials are reported to be under development such as vaccines with enhanced delivery (Morein, Hu, & Abusugra, 2004). If the use of these types of medicines or feeds were permitted, toxicological information on any possible accumulation of drug/feed nanocomponents in food animals must be established. Metabolism of such materials and clearance times would need to be determined to ensure safe levels at time of slaughter. Reliable test methods would need to be established to ensure food safety. Other potential unintentional routes of exposure include the use of water treated with nanomaterials (O'Brien & Cummins, 2010b) in food production and consumption of game/fish from an area contaminated with nanomaterials.

Toxicological effects

Current differences in world legislation on nanotechnologies regarding safety tests to which products are subjected mean that not all products qualify to the same safety standard. Some products may not be widely approved and/or have not had their safety claims tested before they are available on the global market and accessed through the internet. This has created a situation that is difficult to manage with regard to standardising safety testing for an ever increasing number of nanotechnology-related products.

Toxicology research and risk assessments in nanotechnologies are practically non-existent, especially in the food sector (Tiede *et al*., 2008), and few have proved to be valuable in terms of their use in assessing toxicity (Card & Magnuson, 2010). Current toxicity testing approaches used for conventional materials are a suitable starting point for assessing risks associated with nanomaterials, however modifications must be made to account for the differences between conventional materials and nanomaterials. Some nanoparticles have been found to exhibit negative effects on tissues such as inflammation, oxidative stress and signs of early tumour formation (Carlson *et al*., 2008). To determine toxicity profiles, the specifics of the nanoparticle size, shape, solubility, reactivity and other physicochemical parameters must be considered as well as the properties of the substance in a non-nano form. It is likely that toxicological properties vary among particulate nanomaterials, thus a risk assessment must be done on a case by case basis (Munro, Haighton, Lynch, & Tafazoli, 2009).

The safety evaluation of most new substances, according to Handy and Shaw (2007), begins with an overview of physical and chemical properties to ensure safe handling and storage of the material during industrial use and responsible, ethical disposal. Following these basic tests, toxicity of the new substance is studied. Acute and chronic tests, oral toxicity, dermal toxicity, skin irritation as well as mutagenicity tests are carried out on cells.

Some materials exhibit toxicity at the nanoscale and not at the macroscale. For example, Cui, Tian, Ozkan, Wang, and Gao (2005) showed that single-walled carbon nanotubes inhibited human embryo kidney cell proliferation and negatively impacted on cell growth and cell turnover. The nanomaterials involved in this study are unlikely to be used in the food industry, however, such toxic effects must be noted at this early stage of technological development and progress must be cautious.

When looking at the applications of nanomaterials in food packaging and assessing the potential risk of

migration into the enclosed food, tests on chemical migration from food and beverage packaging are a useful reference because they are reproducible, reliable and overall well established. They are relatable to the nanomaterial migration test and can form the basis of a preliminary risk assessment.

These novel materials have the potential to act in a novel way thus novel toxicity reactions may emerge. Maynard (2010) notes that despite nanotechnologies' unique nature, existing knowledge of aerosol behaviour, exposure control and the dangers and physicochemical significance of ultrafines, such as asbestos and crystalline silica, can provide the health impact knowledge that is required as a risk assessment starting point.

Requirements for a risk assessment

The Scientific Committee under EFSA has identified two specific hurdles in performing risk assessments on nanomaterials: difficulty in characterising, detecting and measuring nanomaterials and insufficient information on toxicology data (EFSA, 2009). Pending the progress in the aforementioned problem areas, this Committee recommends a case by case evaluation of specific nanomaterials (Bugusu, Mejia, Magnuson, & Tafazoli, 2009).

Characterisation of nanomaterials is a fundamental requirement of risk assessment. Without an accurate description of a given material, risk cannot be quantified. The scope for complexity among nanomaterials warrants a more detailed characterisation than equivalent non-nano forms and requires the assessment of a range of properties (Maynard, 2010). Standard analysis methods must also be established to detect the presence of nanomaterials in foods and in FCMs. Some such methods are discussed by Tiede *et al*. (2008).

Like information on particulate nanomaterial accumulation in food animals, Handy and Shaw (2007) notes that it is important to know the fate of nanomaterials in the human body following exposure and absorption. Not knowing in which organs accumulation is likely to occur is another hurdle presented to people carrying out a thorough risk assessment.

The convention followed when publishing scientific findings does not support the risk assessor in that many studies aim for a worst case scenario in experimental design to ensure a toxic effect is observed which is worthy of reporting in the scientific community. Although these results are important when carrying out a risk assessment, so too are the "no effect" results that often go unreported. A lot of the nanomaterial exposure studies reported were done on respiratory exposure, perhaps due to an association between asbestos and other ultrafines and getting positive results for inflammatory responses. Many studies do not account for natural inhalation of particles and instead focus on the worst case scenario effect on lung epithelial cells. For a risk assessment to be done on any exposure route related to the food industry, more results for the ingestion of nanomaterials must be reported.

Nanomaterial toxicology studies can be rated using the Klimisch score (Card & Magnuson, 2010). This is the assessment used to rate the reliability of data from such studies in the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) assessment ((EC) No 1907/2006). The system is useful. It can increase transparency in the area by evaluating studies consistently and objectively. To score highly, studies must adhere to comprehensive criteria set by Klimisch.

Regulation of nanotechnologies in the food industry

The regulation of nanotechnologies is within the scope of both so-called horizontal legislation and vertical legislation. Existing horizontal legislation is broad and happens to encompass attributes of nanotechnologies even though it does not specifically aim to do so. Vertical legislation is specifically aimed at regulating nanotechnologies and areas of industries likely to utilise nanotechnologies and so the vocabulary used makes the legislation more applicable to issues faced by users of nanotechnologies. Compared to horizontal legislation, vertical legislation for nanotechnologies is relatively recent and was non-existent until a few years ago.

European horizontal legislation

Directive 2001/95/EC on general product safety, also known as the General Product Safety Directive (GPSD), covers all goods on the market, goods that could potentially be placed on the market and those supplied or made available (including goods supplied as part of a service) to consumers. It provides a definition of a safe product and places the responsibility of ensuring that products are safe on the producers. The safety outlined only refers to human health and not to the environment.

REACH Regulation, (EC) No 1907/2006, was brought into force on the 1st of June 2007. It has changed the control of manufactured and imported chemicals in the EU. Under REACH, the standard information requirements for substances manufactured in or imported into the EU depend on the weight of chemical manufactured/imported per year and the hazard class. REACH is similar to GPSD in that it places the responsibility of gathering intrinsic properties of chemical substances and ensuring chemicals are safe on manufacturers who must provide safety information to consumers by a new labelling style on the product and safety data sheets when requested. Unlike GPSD, however, REACH does take ecotoxicity into account for substances produced/imported over 10 tonnes per year. REACH prohibits the manufacture or sale of any substance in the EU that has not been registered with the European Chemical Agency (ECHA), which acts as the central point for the REACH system.

The classification, labelling and packaging of substances and mixtures are regulated by the Regulation (EC) No 1272/2008. It is additive to the regulation provided by REACH. Users of hazardous substances and mixtures must be informed of the dangers by means of a new labelling system which will include new safety symbols. Safety

data sheets must also be made available to users. If a substance starts being produced at the nanoscale, this could bring about a change in the properties of the substance and therefore a change in its classification. As of December 2010 this type of information must be reported to the ECHA. Although nanomaterials are not specifically mentioned, this regulation is therefore a newly introduced hurdle which chemical producers must contend with in order to produce new substances.

Biocidal products, substances and preparations are covered under the Directive Concerning the Placing of Biocidal Products on the Market (98/8/EC). Nanomaterials are not specifically mentioned as it dates back to 1998; those that demonstrate biocidal effects are in principal under the scope of this Directive but the established risk assessment does not consider nano-specific hazards. The need for revision on this matter is being discussed with particular mention of special testing strategies and methods (UBA, 2009).

European vertical legislation

Legislation in the area of chemicals, cosmetics and food is the first to adapt with the aim of regulating nanotechnologies in their respective areas. The 2004 European Strategy Communication outlined European policy goals in relation to nanotechnologies as being conducive to innovation while also proficient in ensuring its development was responsible and safe (Eisenberger, Nentwich, Fiedeler, Gazsó, & Simkó, 2010). In 2005 the Action Plan for Europe 2005–2009 (COM(2005)243) was additive to the aforementioned paper in that employees were added to the list of risk reduction, public health, safety, environmental protection, consumer protection and the adherence of ethical principles (Eisenberger *et al.*, 2010). Recommendations made in this plan include that particular attention should be paid to limit values, labelling requirements and risk assessment when reviewing items.

In 2007 the First Implementation Report (COM(2007) 505) noted that the lack of data on health and environmental risks was the main obstacle in protecting consumers and the environment. In 2008 the Commission released a communication on Regulatory Aspects of Nanomaterials (COM(2008) 366): central issues in this were similar to previous documents. Opportunities that were presented by the prospect of some nanotechnologies being put to use were weighed up against the potential risks. Existing legislation at the time was deemed adequate to regulate nanotechnologies. The Commission recommendation "On a Code of Conduct for Responsible Nanosciences and Nanotechnologies Research" (COM(2008) 424), issued in 2008, included guidelines for safe, responsible and integrated research which were designed to support countries in the EU in achieving safe and responsible research and to encourage communication on the topic.

Reflecting the developing knowledge in 2009, the European Parliament contested the Commission's opinion that existing legislation was sufficient in a response to the Commission's communication on regulatory aspects of nanomaterials. Later in 2009 the Commission issued the second implementation report (COM(2009) 607) on the "Action Plan for Europe 2005–2009" (COM(2005) 243). In the report it conceded that legislation required adaptation to properly control nanotechnologies, in particular the areas of chemicals, novel foods, food additives and cosmetics. In this it also announced that in 2011 an updated Commission's report on regulatory aspects of nanomaterials will be issued. This will include updates on the instruments of implementation and new legislation which takes international research developments into account. Information will also be made available on uses of various nanomaterials and the relevant safety aspects.

Regulation (EC) No 1223/2009, also known as the Cosmetics Regulation, specifically refers to nanomaterials and offers the first legal definition (article 2, paragraph 1, section k) which was described as being subject to change according to developing research (article 3, paragraph 3). The definition offered notably excludes soluble or physiologically unstable nanoscale systems from the nanomaterial specific notification requirements.

Nanomaterials present in cosmetics must be safe and reported to the commission (article 16). The associated foreseeable exposure conditions must be reported. Specific information must be reported on these products six months prior to being put on the market; this information includes physicochemical specifications, estimated volume to be made available on the market per year, toxicological profile, safety assessment and exposure conditions. The ingredients in nano form must be indicated as such in the list of ingredients by the presence of the word "nano" in brackets (article 19). Although this regulation is for cosmetics and not food, it sets a president for regulation of nanomaterials in consumer products and outlines a need for toxicological data and safety assessment to be conducted before such products are brought to market.

The Regulation on Materials and Articles Intended for Food Contact, (EC) No 1935/2004, regulates food packaging including new types of materials which actively maintain or improve the condition of the food (active FCMs) which is widely viewed as a promising use of nanomaterials. The Regulation allows for the use of active and intelligent food packaging provided the packaging has been shown to be beneficial in terms of food safety, quality and shelf life of packaged foods. Risk of migration is addressed in article 3 where it is noted that FCMs should not transfer constituents to food in any quantity that would endanger human health, change organoleptic properties of the food or deteriorate the food. Authorised compounds are permitted to be released from the FCM and change the composition of the food provided they are compliant with applicable food legislation. Labelling of such systems must comply with the Food Additive Directive (89/109/EEC).

The Food Additives Directive (89/109/EEC) was passed in December 2008 and was the first piece of legislation to

mention nanotechnologies explicitly (Eisenberger *et al*., 2010). Article 12 of this document states that if there is a change in the starting material used or in the production method of an additive (for example, a change of the particle size), it must undergo a new authorisation process and safety evaluation. In addition to this, it is worth noting Commission Directive 96/77/EC which sets limiting standards to the quantity of certain impurities permitted within food additives. It controls the use of food additives, ensuring manufacturers only use approved, quality grades of additives that have passed safety testing.

In the Novel Food Regulation ((EC) No 258/97), novel foods are defined as "foods and food ingredients that have not been used for human consumption to a significant degree within the Community" (European Commission, 2010). Under this Regulation, foods deemed to be novel must undergo a safety assessment prior to being placed on the market. It is thought that the soon to be revised Novel Food Regulation ((EC) No 258/97) will be more specific in terms of nanotechnologies than previous documents.

The Customs services in Finland blocked the import of a food supplement in 2008 based on product claims of increased bioavailability of Vitamin C through nanoencapsulation (FSAI, 2009). The basis for this decision was that the product was deemed a novel food that required a safety assessment and authorisation prior to marketing. A bioavailability increase appears to be positive, however, increasing the bioavailability of a vitamin could have negative repercussions on the health of the consumer. The safe intake level of the more bioavailable vitamin may be reduced compared to the level of the traditional supplement. This and other issues may be the subject of the safety assessment.

The regulation entitled Active and Intelligent Materials and Articles Intended to Come in Contact with Food (EC) No 450/2009, was adopted in 2009. In this it is stated that if legislation limits the quantity of a substance in a food, the total quantity should not exceed this limit regardless of the source i.e. originally included in the foodstuff or following release of that substance from the FCM. If a substance is released into the food in this way, it is required to be included in the ingredients list. For active food substances that are not designed to be released from the packaging and have no function in the food, there is a risk that these substances may migrate into the food. The approach with these types of materials is the same as for plastic materials, which is that these substances should undergo a safety assessment by EFSA and a Community authorisation. Once authorised, the substance can be placed on a positive list and used within specific constraints.

Overview of global legislation

Globally, it can be said that the majority of legislation dealing with nanotechnologies tend to be cautious towards potential risks posed by the new applications whereas the attitude to nanotechnology differs in Taiwan where they have introduced the Nano Mark System: this is a quality-like symbol of assurance to consumers which certifies that a product uses a genuine nanotechnology (Chau *et al*., 2007). Food is not included as a category to which this symbol is assigned, but "nanoingredients" are.

In Australia, like Europe, nanotechnologies are regulated by horizontal legislation (Lyons & Whelan, 2010). NICNAS, which regulates chemicals for the protection of human health and the environment, has recently introduced new administrative processes to address nanotechnology (NICNAS, 2010). NICNAS determines volumes, types and data holdings of nanomaterials being used in Australia and has the responsibility of determining if legislation is sufficient to protect people from potential risks arising from nanotechnology. In this way NICNAS monitors changes in industrial usage and can legislate accordingly to ensure legislation remains at the forefront of developments and to ensure emerging challenges in industrial chemical regulation, including the challenge of nanotechnology, are under control (Mittal, 2010).

In the United States, multiple federal agencies regulate products associated with nanotechnologies and nanomaterials, but there is no regulatory framework that provides consistent and comprehensive screening and protections for consumers (Corley, Scheufele, & Hu, 2009). The United Sates Food and Drug Administration's regulatory framework is challenged by the complexities of nanotechnologies and it is thought that risk assessment research is not progressing at a sufficient rate to deal with advancements in nanotechnologies (Corley *et al*., 2009). Bowman and Hodge (2006) concluded that a regulatory gap existed between commercial developments and public expectations about regulatory protections for nanotechnologies.

Public perception

Public perception of the various applications of nanotechnologies is a major factor determining the commercial success of that field. Consumers' attitudes are particularly sensitive when it comes to the foods and beverages they consume. Whether the benefits that nanotechnologies offer outweigh the risks they present will dictate consumer opinions and willingness to purchase. Participants in a study were hesitant to buy nanotechnology-related foods or food with packaging enhanced with nanotechnologies (Siegrist *et al*., 2007). It was found that public knowledge about nanotechnologies in general was limited in the United States (Cobb & Macoubrie, 2004), but the results show that perceptions were generally optimistic. In Europe it was found that perceptions were less positive (Gaskell, Eyck, Jackson, & Veltri, 2005). More recently the perception of nanotechnology utilisation was assessed by Siegrist *et al*. 2007: the examples presented and briefly explained to the subjects were antibacterial food packaging material, a nanocoating that protects tomatoes from humidity and O_2, a bread product containing nanoencapsulated omega-3 fatty acids and a juice with vitamin A encapsulated in starch. The study comprised of 153 consumers and it showed that nanotechnology derived packaging was perceived as being more beneficial than the

nanotechnology-engineered foods, which supports the hypothesis that foods containing nanoingredients are perceived by the public as less acceptable than using nanotechnologies in food production where the nanomaterials are not contained within the foods, i.e. the use of nanopackaging (Siegrist *et al*., 2007; Sozer & Kokini, 2009).

Conclusion

Ever increasing competition in the food industry has called for lateral thinking in the areas of research and development. The exchange of information across a network of research facilities should make the advancement of nanotechnologies more efficient and could prove very advantageous for the food and food-related industries. Technologies exist, ready to be put to use, in a variety of areas in the food industry. They have the potential to enhance companies' product ranges and expand their geographical market boundaries. Nanotechnologies must be made more accessible to industry and to do this must be presented at later stages of development i.e. "ready to go" ideas and products. However, regulatory issues must be addressed before industry adoption. To generate these well-developed ideas and products, production and/or importation of nanomaterials must be facilitated and regulated based on the principles of risk assssment. When nanotechnologies begin to be embraced by the public and the industry their use will increase exponentially as food companies look for competitive advantage over competitors. If the image of nanotechnologies is presented in a favourable way to consumers, and is accepted over traditional products, this may further increase uptake of these technologies by more reluctant food producers.

Risk assessment, exposure assessment and risk management are all urgently required for existing products available on the world market. Existing uncertainties for risk assessment and exposure assessment of nanomaterials arise due to limited information on several aspects including toxicity, behaviour and bioaccumulation. These uncertainties also have implications for the effective regulation of the use of nanomaterials. Integration at a research level may serve to overcome the nomenclature and protocol issues associated with research in nanotechnology. It is argued that segregation of the various areas involved in the establishment of nanotechnology in the various industries is an inferior research model.

Over the last decade in particular, research has been ongoing into various aspects of nanomaterial toxicology, the assessment process used in the European REACH assessment to assess toxicology studies is a positive step. Published and emerging studies and their findings must be put in perspective; using the REACH assessment process is a way of doing this. It is also a useful tool at the experimental design stage as it clarifies what information is necessary for the production of an impactful toxicology study. It allows the scientific community to take stock of what resources they have in terms of reputable toxicology data.

It is undeniable that nanotechnologies present many beneficial applications to the food industry; so far some of the more developed applications include: improved supplements; novel food packaging and targeted crop pesticides. The reviewed applications may also have positive implications for people in developing countries, particularly in the area of increased agricultural productivity, improved food and water safety and nutrition. Lack of investment in these countries could mean that the benefits of these technologies may be limited to developed countries. It is clear that these new technologies, if managed and regulated correctly, can play a central role in improving product and process development to the benefit of human health and well being.

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